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APPLICATION OF UWB AND MIMO WIRELESS TECHNOLOGIES TO TACTICAL NETWORKS IN AUSTERE ENVIRONMENTS

by

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September 2010

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APPLICATION OF UWB AND MIMO WIRELESS TECHNOLOGIES TO TACTICAL NETWORKS IN AUSTERE ENVIRONMENTS

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This thesis explores the utilization of several different types of wireless penetration technologies as an effective means to counter the extreme Radio Frequency (RF) propagation conditions in austere environments. By extending the range and enhancing the available bandwidth at the edge of a tactical network, the warfighter's technological capabilities become enhanced to meet the demand of the information age. Since the concern is adapting technologies to conquer the rigors of an austere environment, this thesis predominantly evaluates UWB and MIMO technologies at the physical and data link layers by researching both employment capabilities into a tactical network and developing data for analysis through various simulations in these types of conditions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOR	Area of Responsibility
API	Application Program Interface
AWICS	Aircraft Wireless Intercommunications Systems
BER	Bit Error Rate
BLAST	Bell Laboratories Layered Space-Time
BPSK	Binary Phase Shift Keying
CADRG	Compressed ARC Digitized Raster Graphics
CDMA	Code Division Multiple Access
COMMCON	Communication Control
COMSEC	Communication Security
COTS	commercial off-the-shelf
dBm	Decibel (referenced to milliwatts)
DIU	Device Interface Unit
DoD	Department of Defense
DoN	Department of Navy
DSP	Digital Signal Processing
DTED	Digital Terrain Elevation
DVR	Digital Video Recorder
EEN	Electromagnetic Environmental Noise
FCC	Federal Communications Commission
GB	Gigabit
GHz	Gigahertz
GIG	Global Information Grid

Gbps	Gigabits per second
GOTS	government off-the-shelf
HTML	Hyper Text Markup Language
IEFT	Internet Engineering Task Force
IFV	Infantry Fighting Vehicle
IP	Internet Protocol
IR	Infrared
IRC	Internet Relay Chat
IT	Information Technology
ITU-R	International Telecommunication Union Radio
Kbps	Kilobits per second
LLNL	Lawrence Livermore National Laboratories
LOS	Line of Sight
LPI/LPD	Low Probability of Intercept and Detect
MAINGATE	Mobile Ad hoc Interoperability Network Gateway
MANET	Mobile Ad Hoc Networking
MB	Megabit
MBOA	Multi Band OFDM Alliance
Mbps	Megabits per second
MFP	Mobile Foot Patrol
MHz	Megahertz
MIB	Management Information Bases
MIO	Maritime Interdiction Operation
MIMO	Multiple In/Multiple Out
mW	milliwatt

NCO	Network Centric Operation
NCW	Network Centric Warfare
NLoS	Non Line of Sight
NPU	Network Processing Unit
NPS	Naval Postgraduate School
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On Off Keying
OSI	Open Systems Interconnection
PAM	Pulse Amplitude Modulation
PPM	Pulse Position Modulation
PSD	Power Spectral Density
PTP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCA	Radio Coverage Area
RNIC	Radio Network Interface Control
RF	Radio Frequency
SA	Situational Awareness
SINCGARS	Single Channel Ground and Airborne Radio System
SISO	Single In/Single Out
SLA	Service Level Agreement
SME	Subject Matter Expert
SNR	Signal-to-Noise Ratio
SNMP	Simple Network Management Protocol

SPEED	Systems Planning Engineering & Evaluation Device
SURC	Small Unit Riverine Craft
TDMA	Time Division Multiple Access
TLM	Topographic Line Map
TNT	Tactical Network Topology
TOC	Tactical Operation Center
TRANSEC	Transmission Security
UAV	Unmanned Aerial Vehicle
UGS	Unattended Ground Sensor
USB	Universal Serial Bus
UWB	Ultra Wideband
VoIP	Voice over Internet Protocol
WLAN	Wireless Local Area Network
XML	eXtensible Markup Language

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I. INTRODUCTION

A. BACKGROUND

Recently, the Marine Corps published their Communication Control (COMMCON) strategy as a roadmap for their services to eventually migrate to a Network-centric, interoperable network by 2025. The Marine Corps desires the ability to effectively manage and control tactical MAGTF networks; however, current issues with bandwidth constraints and certain austere environments limit the overall effectiveness of their tactical networks [United States Marine Corps, 2010]. The Marine Corps is not alone in their desires. Net-centricity is still the overarching goal within the Department of Defense (DoD), and Department of the Navy (DoN). The purpose of net-centricity is to enable authorized users access to available data on a network. The Network-Centric Operation (NCO) concept covers the entire military response to the Information Age including ways of thinking, human and organizational behavior, and the networks we use across the tactical, operational, and strategic levels of warfare [Silbaugh, 2005]. NCO creates an information advantage for the warfighter by providing an available and protected tactical network infrastructure that enables responsive information-centric operations using dynamic and interoperable communications and computing capabilities. In a broad sense, NCO is about harnessing networks and networked forces to create military advantages and capabilities; therefore, the DoD's ability to understand the requirements levied on our networks is paramount to achieving NCO.

Network-Centric Operations ultimately cannot progress without achieving an effective interoperable communication infrastructure for tactical networks in every environment. For this reason, the DoD must understand the implications of these requirements in all different types of environments and be able to determine how best to implement our communication technologies within the tactical networks in order to achieve NCO. In current real-world operations, a preponderance of our military tactical networks rely heavily on direct Line of Sight (LoS) communication technologies in order to receive and transmit data to the warfighter on the tactical "edge" of the battlefield. For

example, satellite communications, though expensive, can offer highly predictable and stable line of sight coverage of a given area. Hence, the ability to achieve NCO is easier in this type of environment because the technology allows for larger availability of bandwidth and makes the availability of data accessible to those mobile forces widely dispersed upon a non-contiguous battlefield operating at very high operational tempos. Exploiting this type of technology achieves the desired environment for Net Centric Warfare (NCW), and makes sense when operating in areas where radio propagation in not too affected by the environment. However, the military will not be always be operating in these favorable conditions. When it comes operating in an austere environment comprised of thick triple canopy and high precipitation, direct LoS will not meet military communication requirements. Alternate communication technologies need to be explored in order to achieve NCO and provide the means for the warfighter to access required data on the tactical network's "edge".

By the exploration of different radio technologies within an austere triple-canopy environment, the DoD can essentially determine the effectiveness of current radio capabilities and address employment challenges. Whether choosing proper frequencies or determining alternative antenna techniques, the understanding of varying radio propagation effects can help exploit the practical applications for adequately deploying certain radio capabilities or technologies within this type of environment. Radio waves at different frequencies propagate in different ways. They are also affected by factors such as: reflection, refraction, diffraction, absorption, polarization and scattering. The triple canopy environment compounds these factors by limiting the direct line of sight (LoS) on the tactical edge and sustaining higher rates of precipitation. There are several types of technologies showing promise in extending the tactical edge of the network and allowing for the availability of data to increase in this type of austere environment. Two already available for application are Ultra Wideband (UWB) and Multiple-In/Multiple-Out (MIMO) radio technologies.

Ultra Wideband radios have the potential to address the above technological challenges because UWB utilizes extremely wideband signals typically using ultra-short pulses which allows for wave penetration. Radios with MIMO technologies use multiple

antennas at both the transmitter and receiver to improve communication performance that allows the wavelength to create multiple paths thereby increasing spectral efficiency and increasing its effectiveness for Non-Line-of-Sight (NLoS) requirements. Once these underlying physical layer technologies on the tactical "edge" are established, application layer possibilities will emerge that may allow for greater network-centricity on the tactical network, the Global Information Grid (GIG) or the Department of Defense (DoD) systems of the future.

B. OBJECTIVE

This thesis intends to explore the utilization of several different types of wireless penetration technologies as an effective means to counter the extreme RF propagation conditions in austere environments. By extending the range and enhancing the available bandwidth at the edge of a tactical network, the warfighter's technological capabilities become enhanced to meet the demand of the information age. Since the concern is adapting technologies to conquer the rigors of an austere environment, this thesis intends to predominantly evaluate UWB and MIMO technologies at the physical and data link layers by researching both employment capabilities into a tactical network and developing data for analysis through various experiments in these types of conditions.

The thesis addresses several of the major challenges and requirements confronting a commander employing a tactical network in this type of environment. Focus of study is directed on the background of UWB and MIMO technologies and how their characteristics will address these challenges and requirements. This thesis provides specific recommendations for using either the UWB or MIMO technology to counter the effects of radio propagation in an austere environment. The ultimate objective is to analyze constraints associated with radio technologies in an austere environment and develop an integration scheme to expand the tactical network. By capturing data of both capabilities through comparative analysis, modeling and simulation, this thesis will provide the Department of Defense (DoD) a framework to better understand the effects a

triple canopy environment has on radio technologies and aid in the pursuit of a viable solution for extending the tactical network in support of the warfighter during this information age.

C. RESEARCH QUESTIONS

My primary research question explores the most effective means to provide the physical layer link for the warfighter or commander requiring information on the tactical "edge" during this triple canopy battlefield environment. It is of primary importance that the tactical network supports the operational needs to the fullest extent. Therefore, the ability to develop increasing data capabilities for sensors or voice communications by using wireless penetration radios is critical in achieving Net Centric Operations. Through cooperation with personnel at Lawrence Livermore National Laboratories (LLNL) and Silvus Corporation, I was able to model UWB and MIMO technologies and develop a testing plan for researching viable physical layer solution to extend the warfighter's tactical network. Based on the results of the model, I draw conclusions on their capabilities to minimize the affect radio propagation and provide integration possibilities of these technologies into a tactical mesh topology.

1. Primary Question

Given an austere environment with thick vegetation and precipitation, a specified distance between transmitter and receiver, and certain multiple access techniques, how will each wireless radio technology maximize the available bandwidth for the warfighter and extend the tactical edge in the network?

2. Secondary Questions

Secondary questions are as follows:

-What is UWB and MIMO technology?

-What makes UWB and MIMO technology so effective in an austere environment?

-Can UWB or MIMO radio adequately facilitate the minimum bandwidth requirements for military-structured units on the tactical edge of the network?

-What is the optimal network platform required to properly manage Quality of Service (QoS) issues to ensure that optimal service is maintained in this network environment?

-How can UWB and MIMO multiple access techniques be implemented into a tactical mesh topology?

D. SCOPE AND LIMITATIONS

This thesis focuses on comparing wireless penetration devices and their capabilities when faced with severe RF propagation conditions. This was accomplished through literature research, modeling and simulations, and observations during Tactical Network Topology (TNT) and Trident Spectre exercises. Some additional time was required beyond the TNT exercise time slots due to time constraints of the thesis. The modeling and simulations leveraged the information discovered during the literature review process. The scope of the thesis is wide in range to allow for follow-on work. The ultimate goal was to develop a comparative analysis model and incorporate radios into the overall tactical network for future testing in a triple canopy type scenario.

The technical side of the thesis includes development of a model to compare/contrast UWB and MIMO technologies for implementation into a tactical network. This model was designed to collect data and examine how both types of radios handle the affects of radio propagation in this resistive type of environment. In the end, the analysis provides data for developing an UWB or MIMO implementation model for future TNT exercise.

The non-technical aspect of the thesis is the literature review and research to properly account for UWB and MIMO capabilities and the effects of RF propagation in the austere environment. There is also a need to develop, coordinate, and implement a

plan for experimentation of the two radio radios followed by the integration of the most desired radio into future testing environment during future TNT Maritime Interdiction Operation (MIO) exercises.

E. METHODOLOGY

My methodology includes extensive literature research of several wireless penetration technologies, both electronic and hard copy, as well as the guidance provided by Subject Matter Experts (SMEs) in UWB technologies from LLNL and MIMO technologies from SMEs at Silvus Technologies. This allows for the development of critical background material related to UWB and MIMO technologies and how their characteristics address these challenges and requirements.

Once research was completed, a model was developed for testing and comparing these two different radios in an austere environment. The modeling scenario tests for UWB and MIMO capabilities the warfighter might require on the battlefield's edge. Based on the results, performance limitations of the wireless penetration technologies are identified. Once identified, a comparison analysis is generated based on both technologies. The desired end state is to develop an architectural model for incorporating the optimal capability into a tactical network.

F. THESIS ORGANIZATION

This thesis is organized into five chapters. The present chapter is the thesis introduction. Chapter II provides an overview of radio propagations in an austere environment. Chapter III provides an overview for which types of wireless penetration technologies minimize these affects for an austere environment. I will discuss wireless penetration technologies inherent characteristics and capabilities and how they pertain to an austere triple canopy setting. Additionally, I will describe the currently available wireless military radio applications and address any problems that will be foreseen during the upcoming field experiments. Chapter IV addresses the objective of the model and simulation, explains the development and methodology for the model, problems that were encountered that significantly affected testing, and the detailed findings and results of the

modeled UWB and MIMO technologies. Chapter V explores the application and integration possibilities for wireless penetration radios in the tactical network or within the GIG. In addition, any standalone ground, aerial, or space systems that have potential military relevance into the tactical network is also explained. Chapter VI presents a summary of the conducted work, the conclusions and suggestions for further research.

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II. RADIO PROPAGATION IN AN AUSTERE ENVIRONMENT

A. INTRODUCTION

In this chapter, the theoretical basis behind radio propagation within an austere environment and the different wireless penetration technologies to remedy their effects is introduced. The concepts of different wireless propagations, such as absorption, reflection, scattering, refraction, diffraction, and multipath, will be introduced in order to develop a foundation for a comparative analysis and experiment.

B. RADIO PROPAGATION AND EFFECTS

If you want to design an efficient wireless communication system in a triple canopy environment, even for operation over relatively short distances, you need to understand the behavior of radio propagation associated with this environment. In a vacuum, radio waves propagate at 3.108 m/s; however, in any other medium the Radio Frequency (RF) signal propagates differently [Laderriere, Heddebaut, Prost, Rivenq, Elbahhar, & Rouvaen, 2008]. RF signals can become stronger or weaker depending on how they react to different materials, or how they interfere with other signals. This understanding of the different wireless propagation is directly related to the employment of the proper wireless technology. The following discussion is based, unless otherwise noted on [(Laderriere, Heddebaut, Prost, Rivenq, Elbahhar, & Rouvaen, 2008), (Carpenter & Barrett, 2008), (Coleman & Westcott, 2009)].

1. Absorption

Absorption is the most common RF behavior when dealing with an austere environment. When a radio wave reaches an obstacle, such as foliage or trees, some of its energy is absorbed and converted into another kind of energy, while another part is attenuated and continues to propagate, and another part may be reflected. Figure 1 shows RF signal absorption. When the incoming RF signal is absorbed, it converts into heat.

This happens because the molecules in the medium through which the RF signal is passing cannot move fast enough to “keep up” with the RF waves.

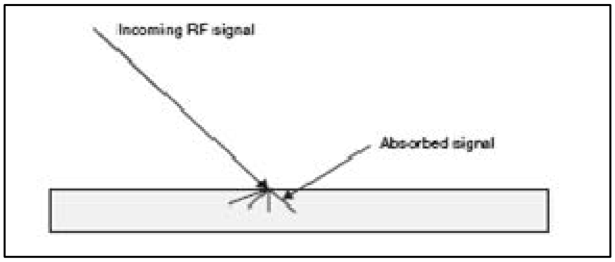

Figure 1. Absorption of RF signal [from: Carpenter & Barrett, 2008]

Lower frequency radio waves travel much easier through dense material, such as trees or stone. However, absorption effects become more important as the frequencies rise. At higher frequencies, absorption becomes a major factor in radio propagation over long-distance transmissions; therefore, one must take careful consideration when determining to use certain frequencies within an austere environment.

Since materials absorb RF signals differently, their rate of absorption needs consideration. Some of the most common types of materials and absorption rates within an austere environment are broken down in Table 1. It seems that the ground and stones produced the highest absorption rate at -15dB; however, the trees and foliage solution rates will most likely increase significantly since the overall austere environment will have heavy, thick foliage combined with multiple layers of dense trees. All of these factors need to be well thought-out prior to deploying wireless technologies in this type of environment. Ultimately, you want to determine which wireless penetration technique is better suited for an austere triple canopy environment and deploy it.

Material	**Absorption rate**
stone/concrete	-15 dB
wood/tree	-4 dB
light foliage	-2 dB
foundation/ground	-15 dB

Table 1. RF absorption rates in austere environments [after: Coleman & Westcott, 2009]

2. Reflection

Even though absorption is one of the most common RF propagations, one of the most important propagation mechanisms is reflection. As illustrated in Figure 2, reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propagating wave [Carpenter & Barrett, 2008]. Reflections can cause serious problem with wireless radios because reflected signals become weaker after being reflected due to some of the RF signal actually being absorbed by the reflecting material. This will ultimately affect the received signal from any type of wireless radio in an austere environment.

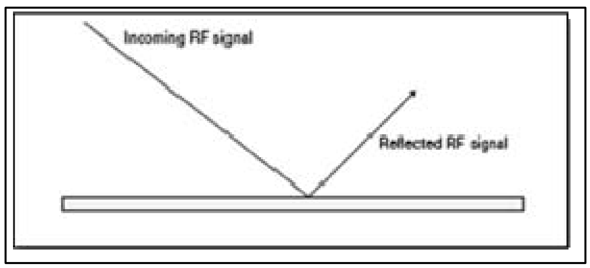

Figure 2. Absorption of RF signal [from: Carpenter & Barrett, 2008]

Reflections can occur from the surface of the earth, rocks, trees or any object within an austere environment as long as the objects dimensions are large than the wavelength of the propagating wave. Therefore, understanding how to calculate the size of a wavelength will give you a greater appreciation for discovering the optimal wireless technology for an austere environment. The formula for this is:

$$l = c/ f$$

Lambda is the wavelength in meters, c is the speed of light and f is the known frequency in hertz. So, when applying this formula to an 802.11g OFDM signal, or 2.45GHz, with the speed of light at 299,792,458 m/sec, the wavelength would be approximately .123 m or 123 centimeters long. This means any object greater in size than this, and has reflective properties, will reflect 802.11b/g/n signal(s).

3. Scattering

Scattering plays a significant role in a triple canopy environment since there are thousands different types of abnormally-shaped objects and minute atmospheric particles within an austere environment. As depicted in Figure 3, scattering happens when an RF signal strikes an uneven surface causing the signal to be forced to deviate from a straight trajectory within the medium, resulting in multiple reflections [Carpenter & Barrett, 2008]. The RF signals become less significant than the original signal, and may even cause a loss of the received signal.

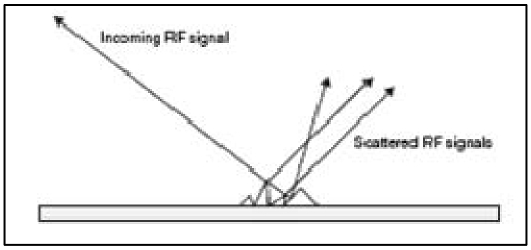

Figure 3. Scattering of RF signal [from: Carpenter & Barrett, 2008]

With all of the thick vegetation, leafy trees, rocks and uneven terrain, this type of forced deviation of the RF signal is the more common and impactful occurrence; however, there is also another different type of scattering. It is called Rayleigh scattering. Rayleigh scattering is a process in which the RF signal moves through a substance and the individual electromagnetic waves are reflected off very small particles [Coleman & Westcott, 2009]. This scattering has a small effect on the signal strength and quality; however, it has to be accounted for since these small particles can be particles, such as sand, water droplets, density fluctuations in fluids, or even dust, can be found in a triple canopy environment.

4. Refraction

Since thick vegetation, foliage, and dense trees will produce a typical NLoS environment, refraction can play a key role in receiving a RF signal around certain objects blocking the Fresnel zone. The Fresnel zone is a theoretical area that envelops

the line of sight (LOS) from the transmitter antenna center of radiation to the receiver antenna center of radiation. If an RF signal changes speed and is bent while moving between media of different densities, it will have implications [Coleman & Westcott, 2009]. Figure 4 shows an RF signal being refracted. As you can see, when refraction occurs with RF signals, some of the signal is reflected and some is refracted as it passes through the medium, and a slight amount of the signal will be absorbed as well.

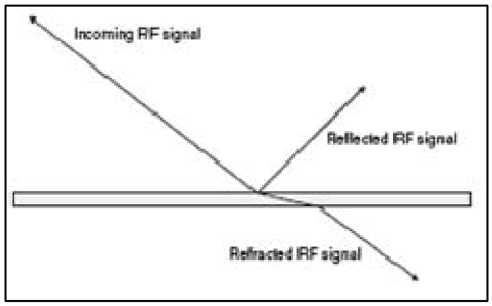

Figure 4. Refraction of Rf signal [from: Carpenter & Barrett, 2008]

Refraction properties are characterized within refraction indexes. Different mediums, such as water vapors or foliage, will have different refraction indexes, and this refraction index helps in determining how much refraction will occur. The different refraction indexes produce variations in the velocity of waves that tend to go further or drop sooner than expected. When the beam passes from a higher to lower refractive index it tends to get bent or refracted away from the normal at the boundary according to Snell's Law, as expressed below. When looking at the formula, θi is the angle of incidence, θt is the angle of transmission, n1 is the refractive index of the first medium (with the incident wave), n2 is the refractive index of the second medium (with the transmitted or refracted wave), εr1 is the relative permittivity of the first medium, and εr2 is the relative permittivity of the second medium.

$$\boxed{\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1}} = \sqrt{\frac{\varepsilon_{r2}}{\varepsilon_{r1}}}.$$

Snell's Law is the main reason for the bending that occurs to RF signals when they pass through a medium, such as air, having a different constant from the medium they just left. For example, since cold air has a slightly higher refractive index than warm air, and normal pressure air has a slightly higher refractive index than rarefied air, the RF signals typically refract slightly back down toward the earth's surface in an outdoor environment [Carpenter & Barrett, 2008].

5. Diffraction

Diffraction is another radio propagation that can prove to be beneficial when confronted with a triple canopy environment. Diffraction is very similar to the propagation mechanism of refraction; however, diffraction is the bending and spreading of an RF signal around an object when it encounters an obstruction [Coleman & Westcott, 2009]. Diffraction occurs because the RF signal slows down as it encounters the obstacle, and this causes the wave front to change directions; therefore, an RF signal that meets an obstacle has a natural tendency to bend around the obstacle as illustrated in Figure 5.

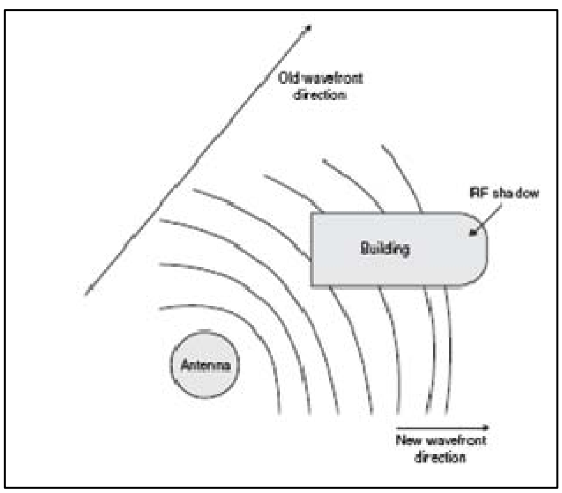

Figure 5. Diffraction of RF signal [from: Carpenter & Barrett, 2008]

Bending changes the direction for some of the RF signal's energy from the normal line-of-sight path, and this change makes it possible to receive a signal from around the edges of an obstacle. Ultimately, the conditions that must be met for diffraction to occur

depend entirely on the size, shape, and material of the obstructing object as well as the exact characteristics of the RF signal [Coleman & Westcott, 2009]. The amount of diffraction also increases with increasing wavelength and decreases with decreasing wavelength; therefore, if the RF signal is smaller than the obstacle, no noticeable diffraction occurs.

6. Multipath

When RF signals bounce around a triple canopy environment through all of the previous mentioned propagation mechanisms, they create multipath. Multipath is a propagation occurrence that results in two or more paths of a signal arriving at a receiving antenna at the same time or within a small fraction of a second of each other [Carpenter & Barrett, 2008]. As shown in Figure 6, the main signal from the transmitting station will travel in a fairly direct route to the receiving antenna; however, the reflected signals from the transmitting station will also travel to the receiving station. Usually, multipath is more commonly associated with an indoor environment when dealing with wireless signals, but when dealing with a triple canopy type environment the amount obstacles are similarly proportionate. The austere environment can produce hundreds of multipath occurrences, and as a result the received RF signal will contain a large number of components from different radio propagation paths.

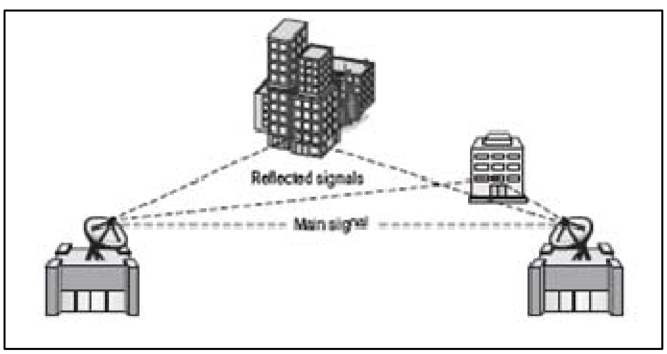

Figure 6. Multipath in an unrban environment [from: Carpenter & Barrett, 2008]

These different radio propagation paths also have different path strength and time delays because the signal components experience different times of reflection and the

propagation routes may be quite different [Coleman & Westcott, 2009]. This leads to multipath fading, which greatly deteriorates the performance of the tactical communications systems.

Multipath fading will have several possible effects. Downfade decreases the received signal due to multiple RF signal paths arriving at the receiver at the same time but out of phase while upfade increases that received signal since the RF signal arrives at the same time and in phase. When two RF signals arrive at the receiver at the same time and are 180 degrees out off phase, they will cancel, or null, each other out [Coleman & Westcott, 2009].

The final effect, called data corruption, is the most commonly faced challenge in high-multipath environment such as the triple canopy environment; hence, it is most critical to understand because this type of environment generates the greatest data corruption. It occurs when the receiver has problems demodulating the RF signal information because of the time between received signals, and this causes a delay spread. As a result, the receiving station will require the data to be resent, and this will eventually start having a negative effect on the throughput and performance of your tactical network.

C. SUMMARY

In this chapter, wireless propagation was introduced based on characteristics important to a triple canopy environment. A triple canopy environment can produce several hundred different obstacles, and this is why multipath is one of the most critical wireless propagation to conquer. Along with conquering multipath, the other propagation characteristics will also require adaption in order to avoid the negative effects, such as data corruption. In the next chapter, several different radio penetration techniques are compared and evaluated in order to find some favorable methods of conquering wireless propagation in a triple canopy environment.

III. RADIO PENETRATION TECHNIQUES IN AN AUSTERE ENVIRONMENT

A. INTRODUCTION

In this chapter, MIMO and UWB technologies will be discussed. This section will explore the history, core characteristics and capacity of UWB and MIMO technology, define their unique features, and discusses how they compare with today's wireless technology. It is the significant difference in bandwidths that will drive many of the fundamental design and performance trade-offs between these two technologies for achieving success in an austere environment including how MIMO and UWB technologies will counter the effects of radio propagation along with establishing how to effectively operate these technologies within a wireless tactical network.

B. ULTRA WIDEBAND TECHNOLOGIES

Despite the many other forms of wireless technology available, UWB technology has plenty of potential and benefits for military use. Ultra Wideband technologies will enhance the overall effectiveness of wireless tactical networks deploying in triple canopy environments and assist the DoD in achieving net-centricity within the GIG. Additionally, UWB is capable of providing very high throughput without the high costs and power requirements of most wireless technologies and can handle extreme radio propagations associated with this type of environment. By using UWB technologies to provide the wireless connectivity for the tactical network, the warfighter will have access to high-speed connectivity in order to transmit and receive mission critical data or voice communication on the tactical edge of the battlefield.

1. History

Some may think of UWB as a new technology or one that has emerged within the wireless industry over the past decade; however, this is not the case. UWB has been around for nearly one hundred years, and around the military for several decades. Figure

7 illustrates the timeline for UWB technologies through the years. It was first employed by Guglielmo Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters [Nekoogar, 2005].

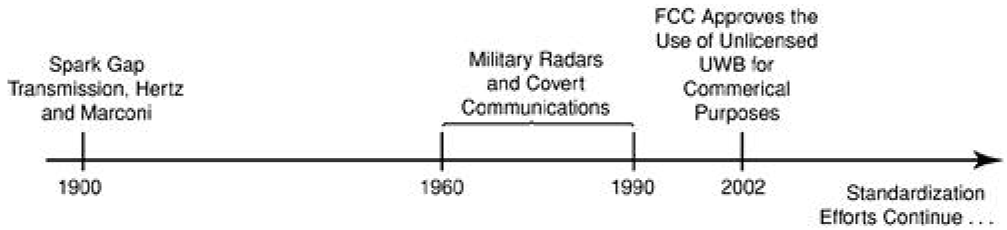

Figure 7. History for events with UWB technologies [from: Nekoogar, 2005]

This same technology stayed around for several decades, but under different names. Ultra Wideband was referred to be such signify synonymous terms as: baseband, carrier-free, and impulse technologies. In the early 1960s, Gerald Ross and K. W. Robins of Sperry Rand Corporation developed this technology to produce modern pulse-based transmissions for military applications on impulse radars [Ghavami & Kohno, 2004]. From the 1960s to the 1990s, UWB technology was restricted to military and DoD applications under classified programs because of it innate security capabilities, and around 1989 the DoD applied the term UWB to these types of systems [Chung & et al., 2005]. Since the 1990s, UWB emerged as a radio transmission scheme for communications, and it was approved in 2002 by the Federal Communications Commission (FCC) of United States for indoor wireless applications [Ghavami & Kohno, 2004].

2. Characteristics

a. General

Ultra Wideband's vast bandwidth provides the foundation on which the core characteristics of UWB technology are built upon. UWB transmitters and receivers are capable of transmitting and receiving millions of time-sequenced, coded narrow pulses (on the order of a few tenths of a nanoseconds) and low power (high-duty cycle of

several hundreds of nanoseconds) over an extremely large spectral mask. These narrow pulses, shown in Figure 8 (a), are sometimes called Gaussian doublet. They are simply a square pulse with some filtering effects to the antennas.

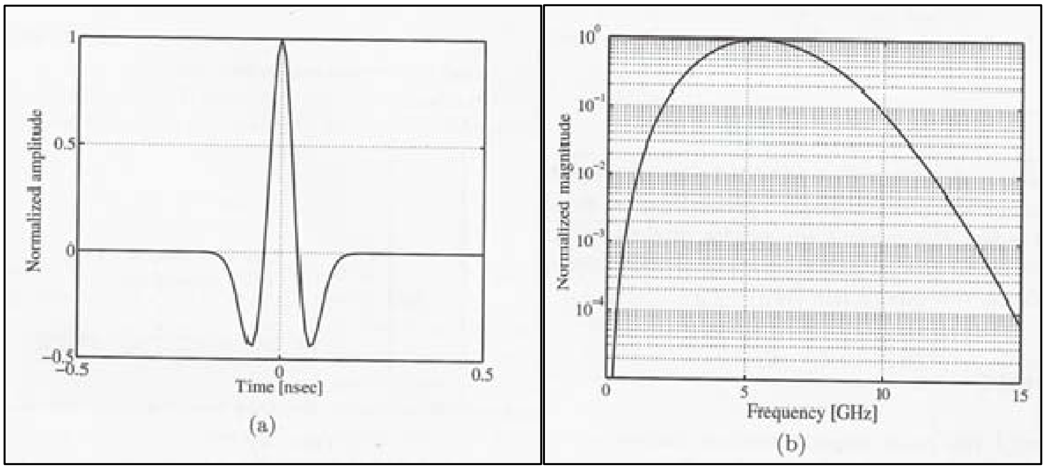

Figure 8. (a) is a UWB pulse shape and (b) is the UWB spectrum pulse [from: Ghavami & Kohno, 2004]

UWB is typically implemented in a carrier-less fashion. Conventional narrowband systems use RF carriers to transmit the signal in the frequency while UWB can directly modulate a pulse that has sharp rise and fall times, and this results in the waveform that occupies several GHz of bandwidth as depicted in Figure 8 (b). Because of this capability, the FCC regulated that systems operating in UWB frequencies will have be limited to this spectral mask and a maximum power requirement in order to try to reduce undesirable levels of interference with other spectrums.

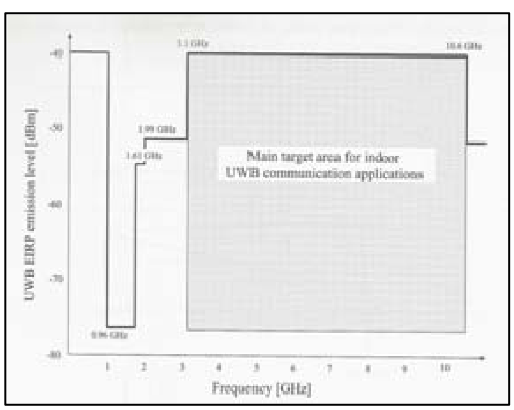

Figure 9. The UWB spectral mask [from: Ghavami & Kohno, 2004]

UWB transmissions must fall within the frequencies of 3.1 to 10.6 GHz, as illustrated in Figure 9, with the bandwidth of the UWB signal is greater than 20% of the center frequency and must have a maximum power output no greater than -43dBm [Federal Communication Commission, 2002]. Therefore, the minimum bandwidth for a 2 GHz UWB centered signal would be 500 MHz resulting in a frequency range of 1.5 GHz to 2.5 GHz and the minimum bandwidth of a 4GHz centered UWB signal would be 1 GHz resulting in a frequency range of 3 GHz to 4 GHz. The corresponding receiver would then translate the received pulses in to data based on the sequence and timing of the pulses. Narrowband technology, on the other hand, has a typical bandwidth of 10% or less. For instance, 802.11b has a bandwidth of 22 MHz with a center frequency in the range of 2.4GHz [Herzig, 2005].

b. Data Rates

High data rates are one of the most compelling benefits for applying UWB capabilities within a tactical network because this will enable those warfighter on the tactical edge the ability to utilize the latest military applications for: video streaming, tracking biometric data, or any other applications requiring real-time informational data with a greater Quality of Service (QoS). Table 2 compares the bit rates and spatial capacity for some wireless technologies used in current tactical wireless networks.

Transmission Distance (m)	**Spatial Capacity (kbps/sq-m)**	**Speed (Mbps)**	**Standard**
10	1000	480	UWB, USB 2.0
10	N/A	200	UWB (4m min)
10	318.3	110	UWB (10m min)
50	83	54	802.11a
100	83	11-54	802.11g
100	1	11	802.11b

Table 2. Spatial capacity comparison and bit rates with wireless standards [after: Ghavami & Kohno, 2004]

UWB's bit rates are at least double that of the fastest 802.11 wireless non-MIMO system and triple the spatial capacity. This is significant since future military applications are going to continue requiring greater bit rates. The capacity benefits can best be explained by looking at the Shannon-Hartley theorem below. The C is the maximum channel capacity (bits/sec); B is the bandwidth (Hz); S is the signal power (W); and the N is noise power (W).

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

This equation tells us channel capacity could increase by increasing bandwidth, increasing the signal power or decreasing the noise. However, you can rule out increasing the power since we will not be able to increase power above the FCC's maximum -43 dBm threshold. Also, you can tell channel capacity (C) linearly increases with bandwidth (B), but only logarithmically with signal and noise. Therefore, having over 7 GHz of bandwidth available for UWB signals, UWB systems appear to have great potential for support of future tactical high-capacity wireless systems since you can ideally achieve data rates in the range of gigabits per second (Gbps) for those warfighters in a triple canopy environment.

c. Transmission Power and Spectral Density

The transmitting power and spectral density of systems using UWB techniques are extremely low compared to other wireless technologies. This is because the power is distributed across the entire ultra wideband bandwidth being utilized while other wireless technologies, such as narrowband or wideband, only use a fraction of this amount of bandwidth. This power spectral density (PSD) concept is expressed as:

$$PSD = P/B$$

Where P is the transmitting power (measured in W) and B is the bandwidth (measured in Hz). Therefore, when you look at some of the different wireless technologies in Table 3

you can see how their spectral density directly related to the transmitting power and bandwidth. UWB has the lowest PSD overall while the lowest narrowband system, the 2G cellular, is nearly 100 times greater in PSD.

System	Transmission power [W]	Bandwidth [Hz]	Power spectral density [W/MHz]	Classification
Radio	50 kW	75 kHz	666,600	narrowband
Television	100 kW	6 MHz	16,700	narrowband
2G Cellular	10 mW	8.33 kHz	1.2	narrowband
802.11a	1 W	20 MHz	0.05	wideband
UWB	1 mW	7.5 GHz	0.013	ultra wideband

Table 3. PSD for wireless communication systems [from: Ghavami & Kohno, 2004]

Additionally, the Figure 10 illustrates how a UWB signal compares with narrowband and wideband signals and where the typical noise threshold might fall. Although the bandwidth is not identical to the Table 3, it still translates to having a PSD below the noise floor, and this characteristic also allows for the coexistence multiple signals within certain spectrums. This extremely low PSD characteristic makes UWB appealing to military application in tactical networks because it will have such a low probability of detection and will increase benefits for security concerns so often associated with wireless networks.

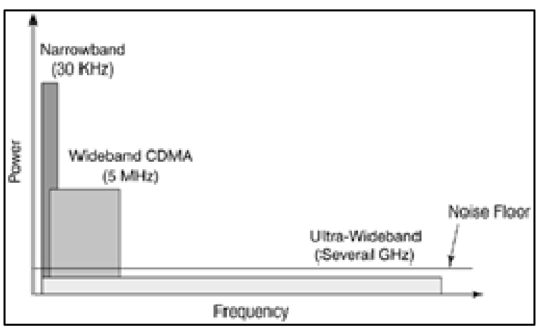

Figure 10. Signal comparison [from: Nekoogar, 2005]

Also, this low PSD translates to UWB systems utilizing less power consumption when operating in a tactical environment and this is critical since the thick vegetation and overhead foliage in a triple canopy environment may restrict to use of certain power supplying capabilities, like solar power for example.

3. Capabilities

From the examination of the characteristics of UWB, several inherent properties arise for exploiting the application of these capabilities within military tactical networks deploying to austere, triple-canopy environments. The most significant capabilities brought about by the UWB technology are its penetration abilities and the excellent multipath mitigation in dense multipath environments.

a. Penetration Abilities

UWB's longer wavelength can be advantageous in a triple canopy environment since UWB transmit signal can penetrating concrete, rocks, trees, or even water. Unlike narrowband technology, UWB systems can penetrate effectively through different materials. The reason is that the low frequencies covered in the broad range of UWB frequency spectrum have long wavelengths and allow UWB signals to penetrate through these different materials [Miller, 2003].

b. Multipath Mitigation and Multiple Access Techniques

The greatest capability for UWB is reducing or mitigating multipath fading and data corruption between tactical nodes within a triple canopy environment. Since the transmission duty cycle of the UWB pulse is so short and the bandwidth is so wide, the reflected pulse has an extremely short window for two pulses to collide. This optimally resolves the multipath propagation and will produce a stable received power signal with minimal fading. Looking at the illustration below, both depicted UWB pulses have less than one nanosecond durations, and they do not overlap; therefore, signal interference will be avoided. As a result, data corruption will be reduced and throughput and performance will be efficiently maintained for the tactical network.

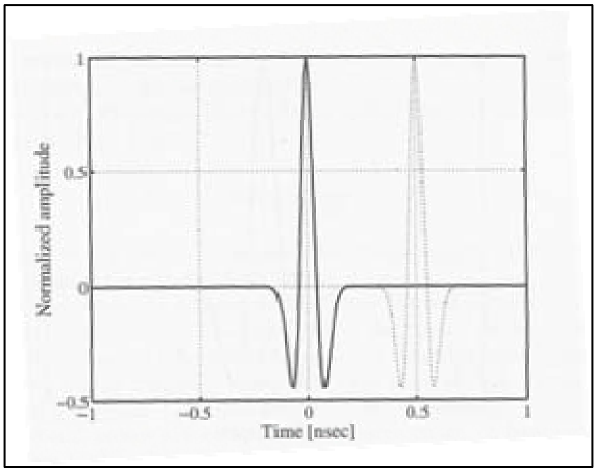

Figure 11. An example of two UWB pulses avoiding signal interference [from: Ghavami & Kohno, 2004]

Although the short duration of UWB pulses makes them less sensitive to multipath effects within a triple canopy environment compared to narrowband signals, it doesn't mean that UWB communications is totally immune to multipath distortion or interference. Depending on the UWB modulation scheme and the band approached used, low-powered UWB pulses can become significantly distorted in these types of environment where a large number of objects are closely spaced [Nekoogar, 2005].

One of the most common types of modulation technique which helps avoid this distortion is Pulse Position Modulation (PPM). With PPM, the data modulates the position of the transmitted pulse within an assigned window in time as shown below in Figure 12. Another popular modulation technique in UWB is Binary Phase Shift Keying (BPSK) due to its smooth power spectrum and low Bit Error Rate (BER). Several others are: Quadrature Phase Shift Keying (QPSK), Pulse Amplitude Modulation (PAM), and On-Off Keying (OOK). All of these various possible modulation options depend on the application, design specifications, constraints, transmission power, QoS, data rates or reliability of channels your UWB system needs to deploy. This is why selecting an appropriate modulation technique is very challenging.

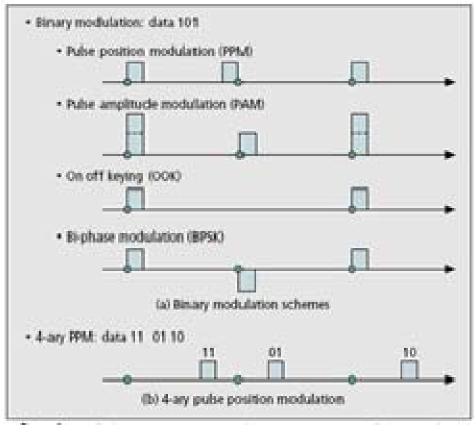

Figure 12. Various UWB modulation techniques [from: Chung & et al., 2009]

Additionally, there is a high probability that UWB signals transmitting from the nodes will overlap since the proximity of the nodes are limited to a given area when multiple UWB nodes exist in an ad-hoc mobile tactical network and they are encircled with trees, foliage, and rocks. This results in distortion of interference; therefore, UWB systems need some type of multiple access technique to manage the co-existences of these nodes. If not, the utilization of UWB technology will not be a viable wireless solution for achieving Net-centricity in a tactical network because the resulting UWB bandwidth will be required to partition their spectrum mask. Once this happens, UWB throughput capabilities become nearly equivalent to narrow or wideband.

In the single-band approach, each radio transmission will occupy the entire spectral mask while the multi-band approach utilizes sections of this bandwidth within the spectral mask. Some of the most common multiple access techniques for the single-band approach are Code Division Multiple Access (CDMA) or Time Division Multiple Access (TDMA). These both allow for better co-existence with other UWB nodes within the Wireless Local Area Network (WLAN); however there are some drawbacks utilizing these techniques [Foerster, Green, Srinivasa, & Leeper, 2001]. TDMA allows several UWB nodes to share the spectrum mask but is limited to certain time slots, and CDMA allows several UWB nodes but will slightly limit the capacity because it shares some of the spectrum mask, some of the time.

For the multi-band approach, the most optimal type of modulation technique for a UWB system in this type of environment is arguably Orthogonal Frequency Division Multiplexing (OFDM). The primary advantage of OFDM over single-band schemes, such as CDMA or TDMA, is its ability to cope with severe channel conditions [Chung & et al., 2001]. OFDM works by splitting the UWB signal into multiple smaller bands, around the 500 MHz limited imposed by the FCC, and then transmitted simultaneously at different frequencies to the UWB receiver [Chung & et al., 2001]. This capability improves the spectral efficiency, has greater resilience to interference, and has the ability to efficiently capture multipath energy. It is also well understood and has been proven in other 802.11 a/b/g/n wireless technologies.

4. Applying UWB to Tactical Wireless Communications and Sensors

The challenge for UWB is trying to get the commercial sector to invest the technology for tactical wireless communication and sensors; however, LLNL continues to strive to advance UWB technologies for potential military uses. Over the last decade, UWB was sought and tested by several different types of tactical communication and sensor systems in order to find solutions for the ever-increasing bandwidth demand that fulfills the need in multi-user communication environments. Some of these systems are: DRACO, AWICS, Hydra UWB, PUMA system, and Trident's UWB unattended ground sensors (UGS) and mesh network system. Even though some of these UWB systems are prototypes, they all exhibit the potential to be very successful in a triple-canopy type environment. Presently, the field of UWB technology has not developed into a mature industry.

a. DRACO System

DRACO is a prototype high-speed multi-user UWB network which incorporates Communication Security (COMSEC) and Transmission Security (TRANSEC) capabilities. As displayed below, the DRACO system is comprised of a Thales multi-band handheld radio, on the right, interfacing with a UWB transceiver and Network Processing Unit (NPU). This system uses OFDM protocols, produces data rates

ranging from 115kbps to 1.5Mbps, and is capable of providing a range of 1-2 km in certain environments [Fontana & et al., 2002]. The beauty of this system is that it does not need a centralized controller since the software internal the NPU autonomously configures the DRACO system to maintain communications with all UWB nodes within the network. In a 2002 field demonstration in Fort Campbell, KY, eight nodes were dispersed with 1 km distance between all of them, and the DRACO system successfully achieved full ad-hoc connectivity [Fontana & et al., 2002].

Figure 13. DRACO UWB Communication Node [from: Fontana & et al., 2002]

b. Aircraft Wireless Intercommunications System (AWICS) UWB Transceiver

Another UWB network radio transceiver is Aircraft Wireless Intercommunications Systems (AWICS) UWB transceiver. It was designed to meet the operational wireless communication requirements of Department of Navy (DoN) onboard Navy and Marine Corps helicopters [Ameti & et al., 2002]. This system needed to provide high enough QoS to guarantee reliable communication for eight users on the airframe. These airframes are capable of providing several multipath conditions from within aircraft fuselage and rotor system. The system, displayed below, is small enough to be worn in a flight suit and rugged enough to withstand wet conditions. The AWICS system used TDMA protocols with a burst rate of 2.048 MHz to accommodate all eight users, and it used an instantaneous bandwidth of 400 MHz with an effective EIRP of +26

dBm [Ameti & et al., 2002]. In 2003, this system produced very favorable results onboard multiple aircraft. The AWICS UWB system robustly maintained communication continuity inside and up to 200 ft outside the airframes.

Figure 14. Prototype AWICS UWB Mobile Transceiver and Headset [from: Ameti & et al., 2002]

c. Hydra Vehicle UWB System

Last year, Hydra developed an UWB vehicular system that was installed in a Russian BMP-3 infantry fighting vehicle (IFV). The high data rate capacity of the UWB system at short range is around 10 meters while long range can achieve communication connectivity over 1 km; however, the data rate is greatly reduced. Hydra claims it can send video over 40 meters at 1Mbps utilizing EIRP [Sweetman, 2009]. This Hydra UWB system is ideal for platoon-level communications because it can link soldiers within a squad inside the vehicles or vehicles-to-vehicle communications with external antennas. The system also is capable of forming a "body area network" linking different soldier-carried electronic systems.

d. PUMA System

Wionic's developed an UWB universal serial bus (USB) high-speed data retrieval system called the PUMA. It is capable of uploading and downloading large amounts of data while attached to fast-moving platforms. During a recent exercise, the

PUMA system was installed on a Raven Unmanned Aerial Vehicle (UAV), depicted in Figure 15, loitering in a very tight orbital track at altitudes around 1000 feet AGL. This is significant, since it is being installed on this small class UAV.[1]

Figure 15. Raven UAV being launched in support of OIF mission [from: Baldor, 2008]

The experiment tested the capability of this system to retrieve data sets greater than 100 MB in a very short duration time. Therefore, the ground data collection point was simulated with a 10 GB digital video recorder (DVR) and a PUMA system. The 10 GB of data was transmitted and collected by a PUMA system on the UAV and transmitted back down another PUMA receiving system connected into the overall tactical network. This system advertises an overall throughput around 110 Mbps, but the effective throughput over the entire 10 GB transfer was between 55-60 Mbps. The overall processing time from ground DVR to complete data transmission into the network for this very large data set was around 6 minutes. In future testing, the PUMA is projecting a higher probability of attaining the desired throughput of 110 Mbps, if the UAV is able to operate at 2000 feet AGL in order to reduce the link interruptions from the look angle exceeding the antenna beam.

[1] PUMA's UWB capabilities and test results from recent governmental exercises were discussed in an e-mail and phone conversations with T. Aytur.

e. Trident's UWB UGS and Mesh Network

Trident System uses an advanced Ultra-Wideband (UWB) communications mesh that provides LPI/LPD (Low Probability of Intercept and Detect). The overall system also provides optimal AES encryption for security. As depicted in Figure 16(a)-16(c), this system combines several scalable UWB unattended ground sensor nodes that provided intelligence, surveillance, and reconnaissance for the tactical edge of the battlefield. The sentry node, depicted in Figure 16(a), is capable of providing data rates up to 250 Kbps for infrared (IR) motion, acoustic, and seismic detection with a range of nearly 300 meters. The recce node, depicted in Figure 16(b), provides data rates up to 5 Mbps for high resolution video and imagery with the same range as the sentry node. The nightwatch node, depicted in Figure 16(c), is used for longer distances between nodes and can establish mesh network connectivity within buildings. It supports up to 100 mesh nodes, supports data rates up 115 Mbps, and has range of up to 1.5 kilometers [Trident Systems, 2008]. Another benefit of using UWB technology for all of these nodes is their long battery lifespan. They all have a battery lifespan of greater than 30 days [Trident Systems, 2008].

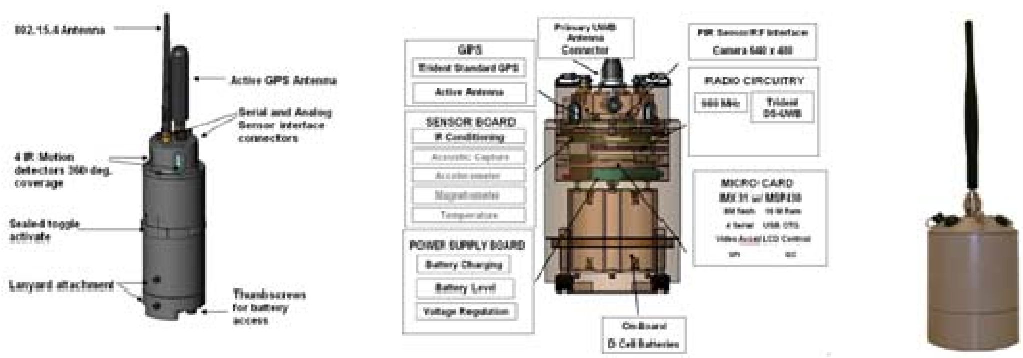

Figure 16. (a) Sentry Node, (b) Recce Node, (c) Nightwatch Node [from: Trident Systems, 2008]

All of these nodes are networked together utilizing UWB wireless technology and mesh protocols. The data is moved throughout the network and connected to other networks via the tactical gateway or Radio Network Interface Control (RNIC). The tactical gateway can be used to transport network data into the Tactical

Operation Center (TOC) and can be used to bridge incompatible waveforms while the RNIC provides an interface between any Windows CE or XP computing device, wireless network, and standard military radio. In the end, this makes this system ideal for the austere environment because the Trident nodes are rugged, easily emplaced, and designed for long-term unattended operation.

C. MULTIPLE IN/MULTIPLE OUT TECHNOLOGIES

Over the last several years, MIMO technology has become quite attractive for military wireless communication systems. Where high multipath propagation environments were once considered an enemy of wireless systems, MIMO technology has enabled wireless systems to leverage this propagation phenomenon in order to create robust communications. MIMO technology uses multiple antennas at the transmitter and receiver to improve communication performance. By utilizing MIMO technology coupled with sophisticated signal processing, wireless radio now have the ability to improve tactical network links in the most demanding and heavily obstructed propagation environments. This capability enables MIMO to produce similar, if not greater, potential than UWB technologies for enhancing wireless tactical networks within a triple canopy environment and achieving the desired DoD’s vision of net-centricity. Additionally, wireless MIMO communication systems can deliver interoperability solutions for existing DoD system since most MIMO technology is based on the IEEE 802.11n or 802.16e standards. 802.11n and 802.16e MIMO technologies can be used with any modulation or access technique. And, they both are capable of providing high data rates on those extended edges of the battlefield, since they increases spectral efficiency by limiting multipath fading and reducing data interference in this type of environment. Therefore, wireless MIMO communication systems, such as 802.11n and 802.16e standards, need to be explored for bridging that proverbial “last mile” on the battlefield.

1. History

Figure 17 illustrates the timeline for MIMO technologies through the years. Back in the mid-1970s, MIMO technology first came into existence with the ideas generated by

A.R. Kaye, D.A. George, and W. Van Etten [Biglieri & et al., 2007]. These ideas led to the publication of several papers being published on several papers relating to beam forming related applications and achieving effective spectral efficiency by Jack Winters of Bell Laboratories in the mid 1980s. In the early 1990s, MIMO technology began to make great strides within the wireless community. In 1993, Arogyaswami Paulraj proposed the concept of spatial multiplexing in wireless broadcast, and this led to the development of the first patent in 1994 [Kaiser, 2007]. He is considered the pioneer of MIMO. In 1996, Gerard J. Foschini refined and developed new approaches to wireless MIMO technology by configuring multiple antennas at both the receiver and transmitter. This MIMO architecture was known as Bell Laboratories Layered Space-Time (BLAST) [Biglieri & et al., 2007]. This represented a significant advance on current, single-antenna systems, and Bell Labs developed MIMO into a laboratory prototype in 1998.

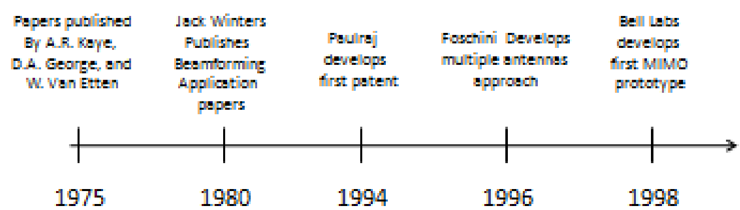

Figure 17. Timeline of events for MIMO technology [from: Kaiser, 2007]

2. Characteristics

a. General

MIMO's ability to utilize multiple antennas within a certain wireless communication system provides the foundation on which the core characteristics of this technology are built upon. MIMO technology exploits the space dimension and multipath propagation to improve wireless communication systems, and this can give substantial capacity gains within the triple canopy environment. As discussed in the history of MIMO, this technology has evolved within the last decade. Instead of just having a single radio chain, which is comprised of the radio with all its supporting

architecture, MIMO systems contain multiple radio chains and each radio chain has its own antenna as depicted in Figure 16. MIMO systems are characterized by the number of transmitter and receivers used by the radio chains.

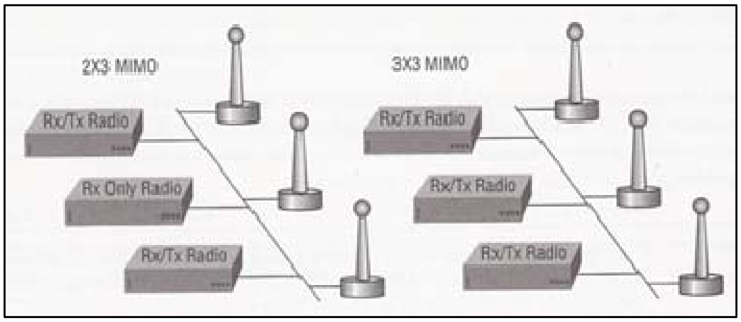

Figure 18. A 2x3 and 3x3 MIMO system [from: Coleman & Westcott, 2009]

Figure 18 depicts two different combinations of radio chains a 2x3 and 3x3. The difference is simply that the 2x3 MIMO system dedicates one radio chain solely as a receiver. The MIMO configurations can be developed as high as a 4x4 system; however, it seems the most common radio configurations within the 802.11n and 802.16e communities deploy either a 2x3 or 3x3 MIMO system. The larger the number of transmitter used, the higher the amount of data is capable of being transmitted via spatial multiplexing. Spatial multiplexing will be discussed later in further detail.

Figure 19 illustrates how two different 2x2 MIMO systems operate using their multiple transmitters and receivers. In the MIMO system to the left, the data is split and each of the transmitters sends the independent data from both of the transmitter radio chains, Tx1 and Tx2, through their different transmit antennas simultaneously and using the same radio channel. Once the signals arriving at the MIMO system on the right, each antenna receives the composite signal from both transmitters and passes it through the receiver radio chains, Rx1 and Rx2. The independent data streams are then recovered by using advanced digital signal processing (DSP) techniques in the MIMO decoder [Liang, 2005]. This process requires an environment rich in multipath, and this is why MIMO systems can excel within the triple-canopy, austere environment.

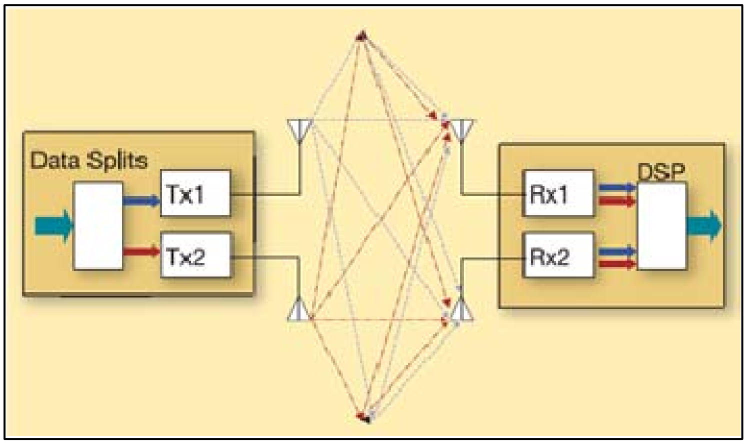

Figure 19. Operational view of a 2x2 MIMO system [from: Liang, 2005]

b. Data Rates

Since most MIMO technology is based on the IEEE 802.11n or 802.16e standards, these standards and their data rates will be discussed in this section.

(1) 802.11n standards. Based on Wi-Fi Alliance's draft for the 802.11n standards, it discusses two bandwidth channels: a 20 MHz and 40 MHz channel [23]. MIMO technologies coupled with wider 40 MHz bandwidth channel and OFDM offer the opportunity of creating a very favorable increase in channel capacity and data rates for the 802.11n wireless systems based on the principles discussed early in this chapter on the Shannon Hartley's theorem. 802.11n radios typically use OFDM. This allows a 20 MHz channel to be divided into 52 subcarriers—48 subcarriers spaced 312.5 KHz apart for data transmission while the remaining 4 subcarriers carry no data and form guard bands between the 48 other subcarriers [Coleman & Westcott, 2009].

MIMO technologies also take advantage of multipath in order to increase the data rate and throughput of wireless communications. It is important to understand that unlike the traditional methods of increasing throughput by increasing bandwidth, MIMO systems can even increase throughput without increasing bandwidth ["Wi-Fi," 2007]. This is capable because each independent data stream is transmitted in parallel from separate antennas, which results in the data throughput linearly increasing with every pair of antennas added to the MIMO system. These principles can be seen in

Table 4. The data rates at least double when comparing the 802.11n 20 MHz channel to the 40 MHz channel. Also, The 802.11n 2.5 and 5.0 GHz data rates go from 15, 30, 45, 60, 90, 120, 135, and 150 Mbps when utilizing just one stream with the 40 MHz channel; however, a second stream is introduced the data rates double to 30, 60, 90, 120, 180, 240, 270, and 300 Mbps, respectively. These rates are comparable to UWB's data rates; however, 802.11n can achieve an even higher data rate. The highest data rates 802.11n that can be theoretically attained utilizing a 4x4 system with two streams and the 40 MHz channel would be 600 Mbps.

	20 MHz Channel		40 MHz Channel	
	1 stream	2 streams	1 stream	2 streams
	Data Rate, in Mbps			
802.11b 2.4 GHz	1, 2, 5.5, 11			
802.11a 5 GHz	6, 9, 12, 18, 24, 36, 48, 54			
802.11g 2.4 GHz	1, 2, 6, 9, 12, 18, 24, 36, 48, 54			
802.11n GI[1]=800ns 2.4 GHz	6.5, 13, 19.5, 26, 39, 52, 58.5, 65	13, 26, 39, 52, 78, 104, 117, 130		
802.11n GI[2]=800ns 5 GHz	6.5, 13, 19.5, 26, 39, 52, 58.5, 65	13, 26, 39, 52, 78, 104, 117, 130	13.5, 27, 40.5, 54, 81, 108, 121.5, 135	27, 54, 81, 108, 162, 216, 243, 270
802.11n, GI=400ns 2.4 and 5 GHz	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	14.4, 28.9, 43.3, 57.8, 86.7, 115.6, 130, 144.4	15, 30, 45, 60, 90, 120, 135, 150	30, 60, 90, 120, 180, 240, 270, 300

Table 4. 802.11 comparative data rate analysis [from: "Wi-Fi," 2007]

(2) 802.16e Standards. When the initial 802.16 standards were first approved in 2001, the standard operated in the 10-66 GHz frequency band and required line of sight towers [Ekland & et al., 2002]. This standard was soon limited in its capacity to achieve the desired results for getting broadband service to rural areas. Therefore, 802.16a was published in 2003. It operated in the lower frequency 2-11 GHz spectrum, used point-to-multipoint or mesh topologies, and did not require line of sight. Eventually, 802.16e was ratified with the helped of MIMO technology.

The 802.16e standard focuses more towards the mobile capabilities. The standard has several channel bandwidths (5, 7, 8.75, and 10 MHz) to be allocated within the 2.3 GHz, 2.5 GHz, 3.3 GHz and 3.5 GHz frequency bands ["Mobile," 2006]. In contrast to the 64 subcarriers used in 802.11n OFDM radio system, 802.16e OFDM is scalable from 512 subcarriers to 1,024 subcarriers with the

corresponding range of channel bandwidths discussed earlier [Parekh, 2006]. For example, a 5 MHz channel bandwidth with 512 subcarriers will have 384 subcarriers to transmit data and 42 pilot subcarriers. The remaining 86 subcarriers carry no data and form guard bands between these 426 subcarriers. Hence, 802.16e has a larger amount of OFDM subcarriers for increased data rates.

Table 5 focuses on more specifically on the 802.16e standards. It represents the data analysis for this standard's highest channel of 10 MHz. This will result in high data rates; although, not near as high as the 802.11n standards since it has a 40 MHz bandwidth channel, and 802.16e is only using 10 MHz. This will be increased to a 20 MHz bandwidth channel with the 802.16m standard. As discussed earlier with 802.11n, the 802.16e radio is also capable of linearly increasing throughput based on the increasing the number of antennas added into the MIMO system. For example, the data rate for the SIMO DL with a 1:1 ratio is 15.84 Mbps but when another antenna is added to form the MIMO DL with a 1:1 ratio, the data rate doubles to 31.68 Mbps. The highest data rate that can be reached while mobile is 63.36 Mbps, although, static positions can achieve data rates close to 100 Mbps ["Mobile," 2006].

DL/UL Ratio			1:0	3:1	2:1	3:2	1:1	0:1
User Peak Rate (Mbps)	SIMO (1x2)	DL	31.68	23.04	20.16	18.72	15.84	0
		UL	0	4.03	5.04	6.05	7.06	14.11
	MIMO (2x2)	DL	63.36	46.08	40.32	37.44	31.68	0
		UL	0	4.03	5.04	6.05	7.06	14.11
Sector Peak Rate (Mbps)	SIMO (1x2)	DL	31.68	23.04	20.16	18.72	15.84	0
		UL	0	4.03	5.04	6.05	7.06	14.11
	MIMO (2x2)	DL	63.36	46.08	40.32	37.44	31.68	0
		UL	0	8.06	10.08	12.10	14.12	28.22

Table 5. 802.16e MIMO comparative data rate analysis [from: "Mobile," 2006]

c. Transmission Power

MIMO technology is capable of exploiting transmission power because of its multiple transmit antennas. Specifically, more transmitting antennas results in a greater ability to transmit more signal. 802.11n and 802.16e technologies have different FCC rules for transmit power. Since they both have narrower bands then UWB, their

transmit power levels are much higher. An 802.11n radio has a nominal transmit power of about 50 mW while the 802.16e has a nominal power of about 10 W [("Wi-Fi," 2007), (["Mobile," 2006)]. Even though the 802.11n is considerably lower the 802.16e, the 802.12n's level of average transmit power is still about 500 times greater than that of the FCC regulated UWB device. This could be a considerable disadvantage if these radios need to be deployed for covert operations within the austere environment.

3. Capabilities

MIMO technologies have some of the same capabilities that were discussed with the UWB technologies; however, MIMO radios achieve them in completely different ways. The following discussion describes how MIMO achieves these capabilities and explains how these capabilities justify why MIMO technology can also make an excellent fit for military applications.

a. Multipath Mitigation

MIMO radios have unique multipath mitigation techniques that exploit the application of these capabilities in military tactical networks deployed in austere, triple-canopy environments. This can be accomplished by calculating the optimal switching points based on the level of multipath propagation being received with the MIMO radio. It then dynamically shifts between the two approaches to offer the necessary coverage or capacity gains demanded from the network at any given time or location [Motorola, 2007].

(1) Spatial Multiplexing. MIMO radios exploit their ability to simultaneously transmit multiple radio signals on different antennas each with carrying different data streams at the same time. One of the critical factors for MIMO systems that needs to be considered is the spacing of the antennas. For most vehicle mounted MIMO radio systems, the minimum antenna spacing will not be a significant factor. However, micro-scaled unattended sensors or UAVs may be limited in their ability to implement MIMO techniques.

Figure 20 illustrates how this technique operates. As the 123456789 signal goes into the radio chain, it splits into three different radios chains: 123, 456, and 789, then simultaneously transmitted. When the signal arrives at the receiver, the three different data streams are recombined into the 123456789 signal using MIMO signal processing. This technique is called spatial multiplexing, and it takes advantage of the multipath environment to provide a very capable means for increasing the channel capacity. For example, MIMO radios are able to best accomplish this when the different paths are spatially distinct with at least a half-wavelength of space between them; therefore, the multipath helps decorrelating the channels and thus enhances the spatial multiplexing capability [Motorola, 2007].

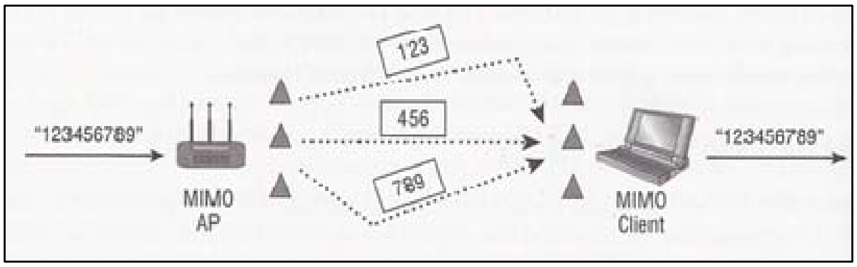

Figure 20. MIMO and spatial multiplexing [from: Coleman & Westcott, 2009]

MIMO radios must also be employed as both, the transmitter and the receiver. If not, spatial multiplexing techniques can't be used, and the MIMO radio would have to fall back to Single In/Single Out (SISO) mode when communicating with other non-MIMO capable wireless radios.

(2) Antenna Diversity. MIMO radios can also survive the negative effects of multipath propagation by applying antenna diversity. In antenna diversity, only one antenna is used at a time, so this should not be confused with multiple-input, MIMO configurations. The MIMO radio attempts to compensate for multipath by utilizing only one antenna instead of utilizing multipath, as spatial multiplexing does. This is accomplished by the MIMO receiver listening to with all its multiple antennas. As the multipath signals arrive at the receiver antennas, the receiver identifies which antenna received the best amplified signal, and antenna selection can change throughout since it is based on the best received amplified signal. The MIMO

radio will also transmit from the same antenna that was last utilized with the best signal. The point to take away from antenna diversity is that by initially employing all the antennas the MIMO radio is considerably increasing its odds of detecting the greatest signal strength and receiving/transmitting uncorrupted data. This is because multiple antennas offer a receiver several observations of the same signal, and each antenna will experience a different interference environment. Thus, if one antenna is experiencing a deep fade, it is likely that another has a sufficient signal. Collectively, antenna diversity capabilities will ensure MIMO radios maintain the robust link for the tactical network within a triple canopy environment.

b. Minimizing RF Footprint with Beamforming

Beamforming is another smart technology capable of reducing MIMO's RF footprint within a tactical environment and increasing range and capacity by focusing the transmission in a coordinated method to the closest known direction of where the receiver is located [Coleman & Westcott, 2009]. Beamforming can increase the power in the direction the signal when transmitting or it can increase receiver sensitivity in that same direction when receiving the signal. This process is quite sophisticated and resource intensive depending on the channel and number of other users on the system; therefore, only 802.11n or 802.16e wireless radios can utilize beamforming in order to maximize this capability [Motorola, 2007]. Switched array and adaptive array are the two distinct capabilities, and they both have properties that reduce the possibility of detection by the adversary while increasing throughput capacity within the tactical network.

(1) Switched Array. Switched array simply uses the MIMO antennas to obtain the best performance. This is accomplished by switching between the many antennas to obtain the greatest number of fixed beam patterns in the general area where the receiver is located in order to achieve the highest signal-to-noise ratio (SNR) [Coleman & Westcott, 2009]. Switched arrays are designed to provide high gain across a

range of signal arrival angles, and can also be used to partition the directions that signals arrive from. This technique is sufficient for MIMO radios that are emplaced or static for long periods of time.

(2) Adaptive Array. Adaptive array is desired for maneuvering MIMO radios because the beam is capable of following in the direction of the received signal. This is accomplished with very small bits of information traveling in the packets of the signal. And, if the MIMO radios receive interfering signals from outside of the desired beam pattern, the radios will reject the interfering signals [Motorola, 2007]. This technique dynamically increase throughput by optimizing receiver sensitivity and transmit power.

4. Applying MIMO to Tactical Wireless Communications

The adaptation of MIMO technologies into tactical wireless communications has been relatively slow. Nevertheless, there are several different types of commercial systems that are being field tested for Defense Advanced Research Projects Agency (DARPA) in order to determine if they can effectively meet some of the tactical wireless requirements. At first glance, these commercial MIMO systems show potential for solving some of the requirements in order to expand the warfighter's bandwidth demand in a triple-canopy environment. These systems are: Motorola's OS Spectra and Silvus' SC2000.

a. Motorola OS Spectra

The Motorola OS Spectra system, depicted in Figure 21, is an 802.16 standard wireless Ethernet bridge very similar to the Redline AN-50e that is currently being utilized by the United States Marine Corps. However, the Motorola OS Spectra looks to be far more superior. It is capable of backhauling the throughput requirements of up to twelve 802.16 base stations on three channels and utilizing the other channels for point-to-multipoint links with minimal performance degradation. It operates in within the 5.725 GHz–5.850 GHz and 5.470 GHz–5.725 GHz frequency bands with a 30 MHz channel bandwidth, and generates a total throughput of 300 Mbps [Tessco, 2007]. It has

an extensive range of up to 120 miles. Also, it is designed to fully integrate with other 802.16 systems, which makes this system easier to manage within the overall infrastructure of the tactical network infrastructure.

Figure 21.   Motorola's OS Spectra [from: Tessco, 2007]

b. Silvus SC2000

The Silvus SC2000, depicted in Figure 22, utilizes 802.11n standard and is the first MIMO wireless system specifically designed for military applications. It utilizes frequencies of 2.4-2.4835 GHz and 4.9-5.8 GHz with channel bandwidths of: 5, 10, and 20 MHz. According to Silvus, their SC2000 surpasses the capabilities of commercial systems by: outperforming in NLoS multipath rich environments, withstanding jamming attacks up to 100 times the commercial system, achieving very high data throughput rates, acting as a mesh network relay, and ensuring connectivity in high mobile ground and air conditions [Silvus Technologies, n.d.]. During field tests in Los Angeles and at NPS's TNT and MIO experiments, the SC2000 delivered 4.5 times more coverage in dense urban terrain and three times the data rate as commercial systems. The data rates ranged from 1.5 to 200 Mbps [Silvus Technologies, n.d.].

Figure 22. Silvus' SC2000 [from: Silvus Technologies, n.d.]

D. SUMMARY

In this chapter, MIMO and UWB technologies were reviewed. The following Table is a comparative analysis from the research:

	UWB	MIMO (802.11n)	MIMO (802.16e)
Frequency	3.1-10.6 GHz	2.4 and 5 GHz	10-66 GHz 2-11 GHz
Bandwidth	500 MHz	5, 10, 20 and 40 MHz	5, 7, 8.75, and 10 MHz
Max Throughput	> 480 Mbps	150 Mbps (20 MHz) 300 Mbps (40 MHz)	63 Mbps (mobile) 144 Mbps (static)
Avg Throughput	Dependent on environment	Dependent on environment	Dependent on environment
Power	1mW	50mW 2 W (Sylvus)	10 W (can select lower settings)
Range	< 300 m (researched < 3 km)	250 m (researched 1.5 km)	10 km (researched 193 km)
Covertness	High	Medium	Medium
Penetration Capable	High	Medium	Medium
Multiple Access	Yes	Yes	Yes

Battery Consumption	Low	Medium	High
Current Usages (researched)	DRACO (comm) AWICS (helo comm) Hydra (IFV comm) PUMA (UAV relay) Trident (UGS and Mesh network)	Silvus SC2000	Motorola OS Spectra
Comments	Civilian restrictions limits power and range	4x4 systems at 40 MHz BW are capable of 600 Mbps	802.16m is expect to get up to 1Gbps throughput

Table 6. An UWB and MIMO technology comparison

Both, UWB and MIMO, technologies have unique features that make them viable wireless candidates to ensure accessibility and reliability and extend the tactical network in a triple canopy environment. Therefore, modeling and field testing these technologies in a triple canopy environment, or one is highly comparable, needs to be conducted. In particular, testing needs to address how well MIMO and UWB technologies counter the effects of radio propagation along with establishing how to effectively operate these technologies within a wireless tactical network. Results should include: throughput capability, reliability, security, and transportability. Planning and analysis of this modeling test will be discussed in Chapter IV followed by a network implementation concept in Chapter V. In Chapter VI, a detailed test plan will be incorporated for future experimentation.

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IV. MODELING UWB/MIMO TECHNOLOGIES IN AN AUSTERE ENVIRONMENT

A. INTRODUCTION

The purpose of this chapter is to capture data for how wireless penetration technologies will perform in a triple canopy environment, as discussed in Chapters II and III. Due to time constraints for the development, preparation, and evaluation of the LLNL's UWB radios and Silvus' MIMO radios, a government off-the-shelf (GOTS) modeling application serves as an evaluation tool. This chapter outlines the details of the GOTS modeling application from simulation development to model results for several different UWB and MIMO technologies. The simulation results will provide an insight for UWB and MIMO application and implementation into the tactical network discussed in Chapter V and further guidance for the development of a future testing plan discussed in Chapter VI.

B. MODEL DEVELOPMENT

Model development was accomplished through the use of a GOTS modular software application called Systems Planning Engineering & Evaluation Device (SPEED). SPEED, pictured in Figure 23, provides IT and communication planners at all levels with a set of tools that can be used to perform a wide range of communications planning, RF engineering, and spectrum management functionality to support the tactical environment [United States Marine Corps, 2010]. The model development's main objective was assessing the connectivity capability of these different radios in a simulated triple canopy environment and ensuring throughput sustainment for a platoon-size element operating in these conditions.

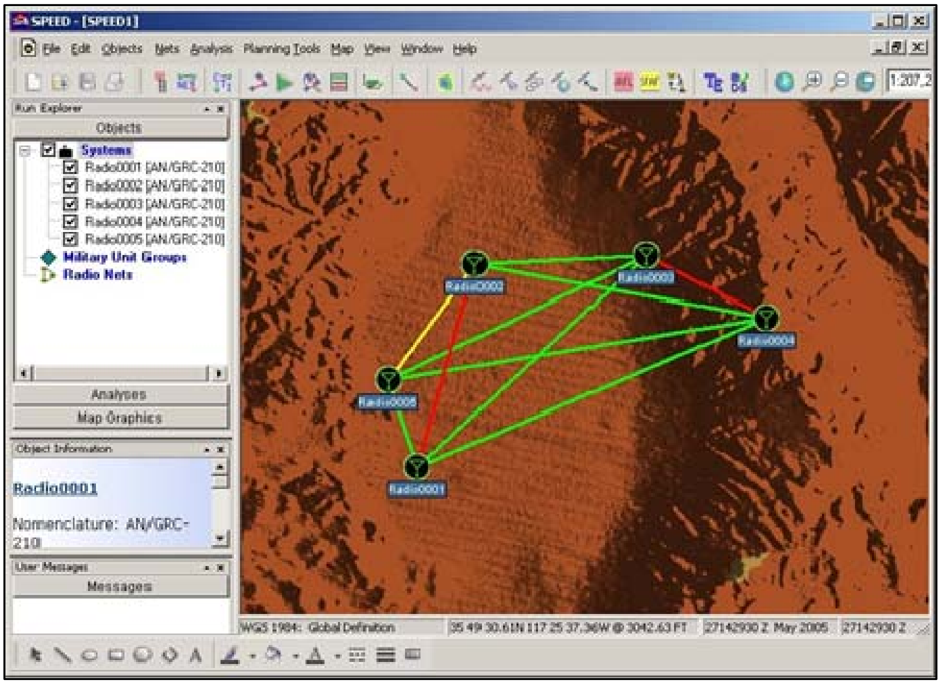

Figure 23. Screen shot from the SPEED modeling application [from: United States Marine Corps, 2010]

1. Type of Equipment and Capabilities

SPEED provided the ability to test most Joint Service radio and antenna assets, but it also allows the user to customize radio and antenna assets. The radios and antennas developed for testing closely mimic the UWB and MIMO radios and antennas researched in Chapter III. This was accomplished through the utilization of physical characteristics discussed along with specification data sheets from the different companies. A majority of the radio data was captured from vendor’s specification sheet; however, their antenna specifications were not clearly defined. Therefore, the foundation for developing antenna parameters was drawn from Table 7. The table shows the different types of antennas that are utilized for UWB and MIMO radios. Each radio's antenna was assumed to be oriented for maximum gain on a given link. For semi-directional antennas, such as the patch/panel, yagi, and sector antennas, the embedded analysis tools provide the antenna azimuth information reference. This ensures the antennas are correctly aimed because if not the signal at the desired receiver will be severely attenuated.

Antenna Types	Horizontal Beamwidth (in degrees)	Vertical Beamwidth (in degrees)
Omni-directional	360	7 to 80
Patch/panel	30 to 180	6 to 90
Yagi	30 to 78	14 to 64
Sector	60 to 180	7 to 17
Parabolic dish	4 to 25	4 to 21

Table 7. Antenna beamwidths for wireless radios [from: Carpenter & Barrett, 2008]

a. UWB Radio System

(1) Transceiver. The UWB transceiver developed for this simulation uses some of Trident's UWB radio system; however, it is important to remember that an UWB transmitter is extremely difficult to mimic because it is sending billions of pulses across a very wide spectrum of frequency several GHz in bandwidth. Therefore, the modulation scheme developed for the UWB transceiver is based on an UWB OFDM solution proposed by the Multi Band OFDM Alliance (MBOA) [Guéguen & et al., n.d.]. Based on MBOA's proposal, the simulated transceiver has a frequency of 3-10 GHz with a receive noise figure of 6 dB. In order to closely simulate OFDM for this UWB radio system, each 528 MHz channel is divided into 122 subcarriers spaced 4.125 MHz apart and will use 507 MHz of the channel bandwidth for data transmission and pilots [Guéguen & et al., n.d.]. Data rates are based on the use of BPSK and QPSK, and data rates were set to 9, 18, and 54 Mbps based on the convolutional 1/2 and 1/3 coding scheme. Using Trident's UWB nightwatch node specification sheet, transmit power for the transceiver was established for 50-500 mW [Trident Systems, 2008]. The receiver has a 528 MHz bandwidth and the SNR will be set between 2-21 dB since UWB has the capability of operating in the noise floor already.

(2) Antenna. There are several different types of antennas that can be utilized with the UWB transceiver. Trident's antenna utilizes a small omni-directional antenna while several of the other systems discussed in Chapter III use a patch

panel antenna. Since the transceiver has more UWB characteristics than the others, an omni-directional antenna was developed. The UWB antenna, in Figure 24, has a vertical polarization and factoring in 6 dBi of mainbeam gain. The antenna size is very similar to the Trident's antenna set at roughly 10 inches. The beam pattern was developed from Table 7. The vertical beamwidth is 60 degrees and the horizontal beamwidth is 360 degrees. The frequency of the antenna was placed from 2.9-10.1 GHz.

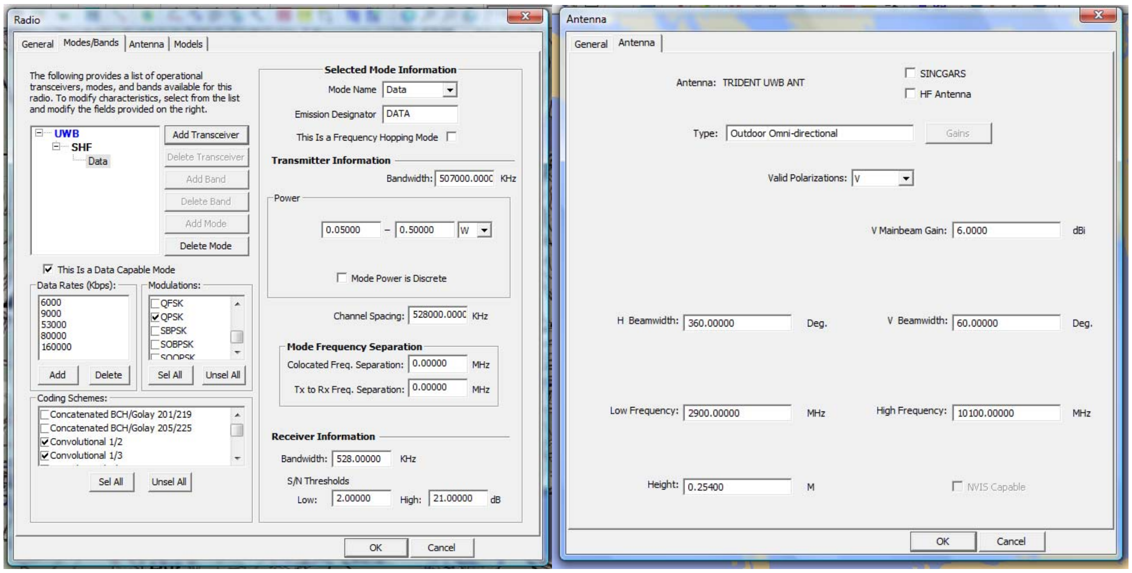

Figure 24. UWB transceiver and antenna configurations in SPEED

b. *802.11n MIMO Radio System*

(1) Transceiver. The 802.11n transceiver developed for this simulation is similar to Silvus' SC2000 2.4 GHz MIMO radio system. The primary focus for this transceiver is data capabilities. The simulated transceiver, displayed in Figure 25, has a frequency of 2.412-2.484 GHz with a receive noise figure of 6 dB. In order to closely simulate OFDM for this MIMO radio system, each 20 MHz channel is divided into 52 subcarriers spaced 312.5 KHz apart and will use 16.6 MHz of the channel bandwidth for data transmission and pilots. Data rates are based on the use of BPSK, QPSK, and QAM. BPSK was set for 9 Mbps, QPSK was set for 18 Mbps and QAM was set 54 Mbps using 64-QAM [Carpenter & Barrett, 2008]. Based on Silvus' SC2000 specification sheet, transmit power for the transceiver was established for 50-1000 mW.

The receiver has 24 MHz bandwidth and the SNR will be set between 8-25 dB since we are looking to get data rates between 5-54 Mbps [Coleman & Westcott, 2009].

(2) Antenna. Silvus' SC2000 utilizes several small omni-directional antennas to produce its MIMO capabilities. The modeling application used in the simulation does not allow for this; therefore, this simulation will be limited to only its beamforming capacity. As discussed in Chapter III, beamforming can increase the power in the direction the signal when transmitting or it can increase receiver sensitivity in that same direction when receiving the signal. This capability is replicated using a type of phased array antennas called a planar array antenna. The planar array antenna is composed of lots of radiating elements each with a phase shifter. By shifting the phase of the signal emitted from each radiating element, beamforming is replicated. The planar array antenna used for the 802.11n transceiver, in Figure 25, has a vertical polarization and factoring in 9 dBi of mainbeam gain. The antenna size is very similar to the SC2000 antennas set at roughly four inches. The beam pattern was developed from Table 7. The vertical beamwidth is 60 degrees and the horizontal beamwidth is 75 degrees. The frequency of the antenna was placed from 2.3-2.5 GHz.

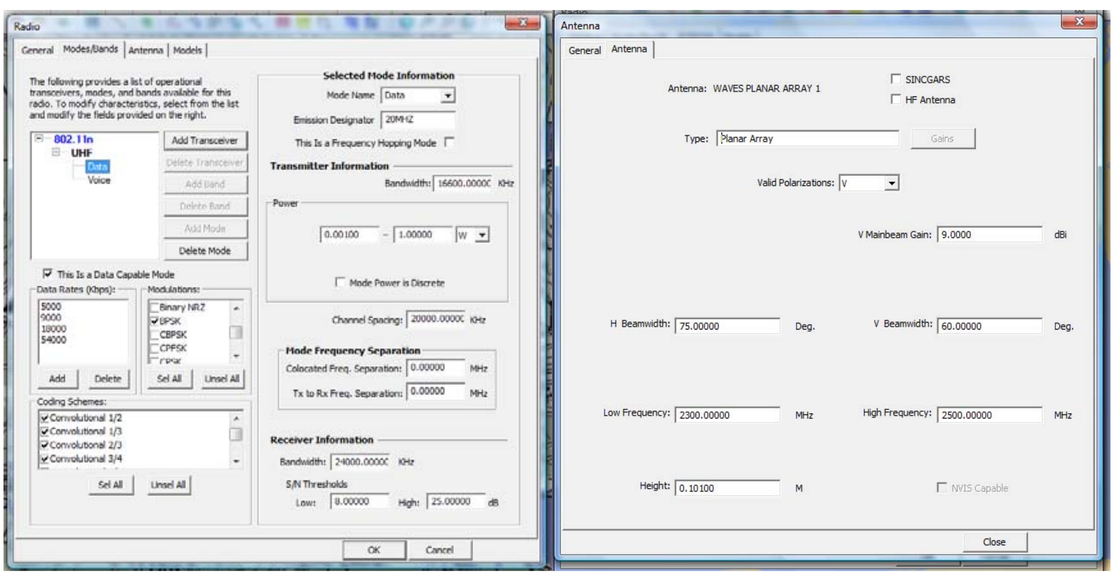

Figure 25. 802.11n transceiver and antenna configurations in SPEED

c. 802.16 MIMO Radio System

(1) Transceiver. The 802.16e transceiver developed for this simulation, in Figure 26, is similar to IEEE 802.16e 5 GHz MIMO radio system. The primary focus for this transceiver is data capabilities. The simulated transceiver has a frequency of 5.725–5.850 GHz with a receive noise figure of 5 dB. In order to closely simulate OFDM for this MIMO radio system, each 10 MHz channel is divided into 1024 subcarriers spaced 11.1607 KHz apart and will use 9.497 MHz of the channel bandwidth for data transmission and pilots [Parekh, 2006]. Data rates are based on the use of BPSK, QPSK and QAM. BPSK was set for 2 Mbps; QPSK was set for 4 and 6 Mbps; and QAM was set 8 and 12 Mbps using 16-QAM [Araújo, n.d.]. The 8021.6e radio devices are designed to start with lower power rates and will increase until radio connectivity is established; therefore, transmit power for the transceiver was established at 250-2000 mW. The receiver has 12 MHz bandwidth and the SNR will be set between 7-25 dB [Araújo, n.d.].

(2) Antenna. The 802.16e antenna is replicated using another type of phased array antenna. The phased array antenna is composed of lots of radiating elements each with a phase shifter. By shifting the phase of the signal emitted from each radiating element, beamforming is replicated. The phased array antenna used for the 802.16e transceiver, in Figure 26, has a vertical and horizontal polarization. Both polarizations factored in 10 dBi of mainbeam gain. The antenna size was at roughly four inches. The beam pattern was developed from Table 7. The vertical beamwidth is 60 degrees and the horizontal beamwidth is 60 degrees. The frequency of the antenna was placed from 5.725-5.850 GHz.

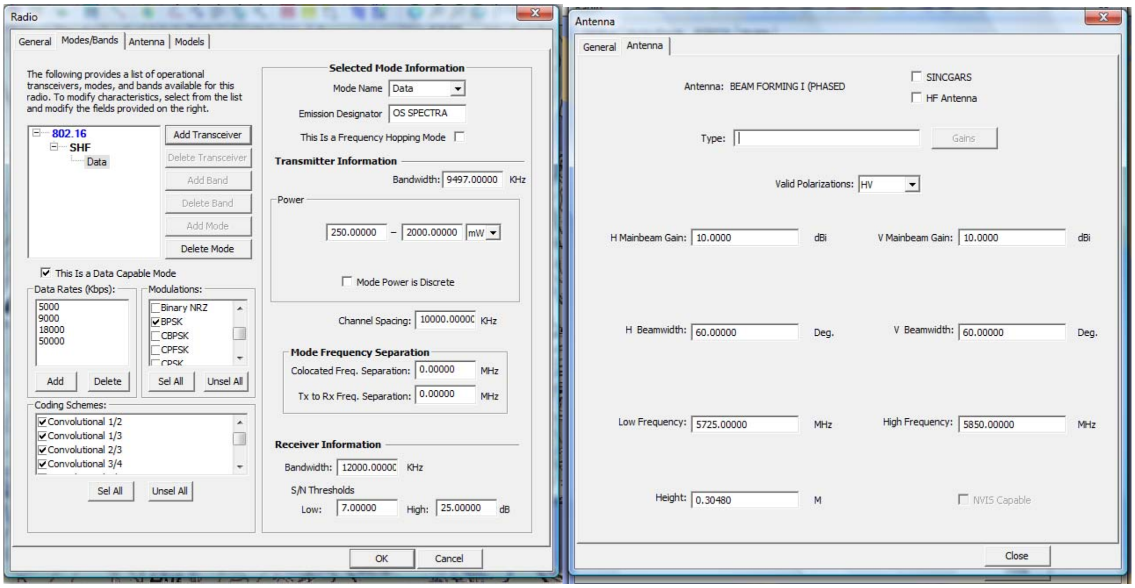

Figure 26. 802.16e transceiver and antenna configurations in SPEED

2. Identified Environmental Conditions

SPEED, illustrated in Figure 27, allows the user to adjust the environmental parameters [United States Marine Corps, 2010]. The simulation link parameters replicate some of the radio propagation that is possibly experienced in an austere environment along with the actual terrain analysis around Fort Benning, GA. The following link parameters were modified during all three technology simulations: humidity, ground type, climate, electromagnetic environmental noise, and surface refractivity.

Figure 27. Customized link parameters for SPEED

a. Humidity

As discussed in Chapter II, water vapor molecules in the atmosphere can produce additional signal attenuation at higher frequencies. Since UWB and MIMO are operating in this range, the simulation needs to account for this radio propagation. SPEED offers several different humidity values. They are: very dry at 0.0 g/m3; dry at 2.5 g/m3; average at 5.0 g/m3; humid at 10.0 g/m3; and very humid at 50.0 g/m3. The value that best simulates an austere environment is the humid [United States Marine Corps, 2010]. Therefore, all three of the radios were tested using this setting.

b. Ground Type

The ground will produce the highest absorption rate when deploying these radios in this environment. This factor estimates the conductivity and permittivity by the selected ground type between two connected radios along a point-to-point path. The ground-type options are: Marsh, Average, Desert, Fresh Water, and Salt Water [United States Marine Corps, 2010]. Marsh was selected for all three radio simulations. An average environment seems the most logical since it is synonymous with a tropical or semi-tropical environment. Also, the ground along the riverbanks was hard, and not marshy, during the most recent TNT exercise at Stennis, MS.

c. Climate

Climate is another parameter that allows SPEED to further simulate. From a list of nine different climate regions stored in SPEED, the best suited for this simulation is Equatorial. This parameter is derived from the following variables: seasonal temperature variations are small, the absolute surface humidity is high throughout all seasons, and annual perception is between 40-100 inches. This parameter is an excellent model for a country like Columbia or Ecuador.

d. Electromagnetic Environmental Noise

Electromagnetic environmental noise (EEN) can limit the performance of receivers. EEN originates from a wide range of sources. In an austere environment,

man-made noise sources can range from gasoline engines on the Small Unit Riverine Crafts (SURCs) to possible high-voltage power lines in an AOR while natural noise sources can range from subterranean transmissions to lightning. This EEN selection is possible in SPEED. Selections range levels from the noisiest (Business Area) to the quietest (Galactic Noise) [United States Marine Corps, 2010]. The EEN selection for all three simulations was the rural area value. This selection accounts for an immeasurable amount of tropical wildlife and its best suits the triple canopy environment.

e. Surface Refractivity

Surface refractivity, as discussed in Chapter II, is the bending of an electromagnetic wave as it propagates through the earth atmosphere. This is mostly controlled by three factors: atmospheric pressure, temperature, and humidity. Thus, the simulation still needs to account for some portion of refractivity even though the radio distances are not exceeding 500 meters. The actual bending is determined by the refractivity gradient (rate of change)—the greater the refractivity, the greater the bending. This parameter is adjusted per radio, and each radio has a refractivity range of 200-450 N-units [United States Marine Corps, 2010]. Since the radio distances are less than 500 meters, the surface refractivity was set at lowest setting (200 N-units) for each radio in all three simulations.

f. Terrain Elevation and Vegetation

All terrain elevation and vegetation data for the simulation was supported utilizing Digital Terrain Elevation Data (DTED) and Compressed ARC Digitized Raster Graphics (CADRG) maps.

(1) DTED. DTED is a series of elevation readings at fixed intervals. The density of these intervals depends on the level of DTED used. DTED Level 1 has a distance spacing of 90 meters and approximately 80% earth coverage. Level 1 is approximately equivalent to the contours on a Joint Operational Graphic (JOG) map [United States Marine Corps, 2010]. DTED Level 2 has a distance spacing of 30 meters, which is more accurate than level 1 DTED, but it has less than 70% earth

coverage [United States Marine Corps, 2010]. Level 2 is approximately equivalent to the contours on a Topographic Line Map (TLM). An example of Level 2 is a 1:50,000 military map. DTED Levels 1 and 2 were utilized for each simulation; however, the focus was ensuring level 2 data to precise terrain data was captured for each simulation.

(2) CADRG. CADRGs are produced from hardcopy charts or maps that are converted into digital data by raster scanning and transforming the map image into the Equal Arc-Second Raster Chart (ARC) frame of reference [United States Marine Corps, 2010]. These digital maps were used specifically for this intended purpose, and each radio was emplaced using these maps as a frame of reference. Since the distance between radios was relatively short, Topographic Line Maps (TLM) for the 1:50,000 were utilized during this simulation.

3. Other Requirements Not Currently Identified

a. Unmodeled Losses

SPEED does not account for the NLoS attenuation due to trees and thick foliage in an austere environment. This will have to be factored into the radio's received signal strength calculated by the modeling application. The attenuation caused by trees varies significantly depending on the shape and thickness of the foliage. According to the International Telecommunication Union Radio sector (ITU-R), the rule of thumb is about 1 dB of attenuation per meter for 5 GHz and about 0.5 dB per meter for 2.4 GHz [Tranzeo Wireless Technologies, 2007]. This attenuation variable will be added to the receiver signal strength of each radio. It should be noted that the receiver signal strength alone is not a good indication of the weakest signal that can be reliably decoded. If the SNR is not sufficient due to a higher noise floor, the radio system may be limited by the noise floor rather than the receiver signal strength.

b. SNR Adjustments

The predicted SNR will need to be adjusted also, since it plays a role in determining the minimum required SNR on a certain bit rate or modulation. Since dBm

is in logarithmic scale, SNR will be obtained by subtracting the noise from the signal strength. The design of the receiver also plays a role in the minimum required SNR for a specific bit rate. All of these SNR were outlined earlier with each transceiver and will be used to ensure reliable decoding for each radio system.

c. *Dynamic Radio Function*

The simulation also does not imitate the MIMO radios dynamic functionality. A dynamic radio system would be able to set the modulation and coding scheme [Coleman & Westcott, 2009]. For example, if the radio's receiver sensitivity is good, a high throughput modulation type such as QAM would be selected. As the user moves further way, the radio's receiver sensitivity would decrease and a lower throughput modulation scheme such as QPSK would then be selected. This dynamic functionality will be accomplished manually at each testing distance.

C. METHODOLOGY

The methodology for evaluating all three radio systems and the environmental model discussed in the previous section was accomplished using SPEED's Point-to-Point (PTP) Analysis. PTP Analysis was used to determine link probability by developing a link budget to account for FSPL, multipath, and the UWB, 802.11n, and 802.16 radio systems properties. This analysis allows the user the ability to optimize the performance of these systems. Since the simulation does not account for the NLoS factors, the additional attenuation will need to be calculated into the received signal along with the SNR to ensure the proper receiver sensitivity for each radio system. The site selected for this simulation was Fort Benning, GA.

1. UWB Radio System

The PTP simulation for the UWB radio is illustrated in Figure 28. The UWB radio parameters established in the previous section are used in this analysis. One radio, UWB 02, has a total antenna height of 8 inches to simulate ground emplacement while the other radio, UWB 01, is set at 3 feet to simulate a radio mounted on a tactical vest.

The range ring around UWB 01 is placed at 300 meters and is used to gauge placement distance. Both UWB radios will be initially placed 300 meters apart for one another. The receiver sensitivity thresholds for a 54 Mbps data rate, QPSK, and convolutional 1/3 coding scheme will be around -71 dBm with a 4 dB SNR [Guéguen & et al., n.d.]. If the radios fail to achieve the desired received signal strength, UWB 02 will be moved closer to UWB 01 until the threshold is established. The TLM 1:50,000 map is used as reference for elevation and vegetation data for this PTP simulation.

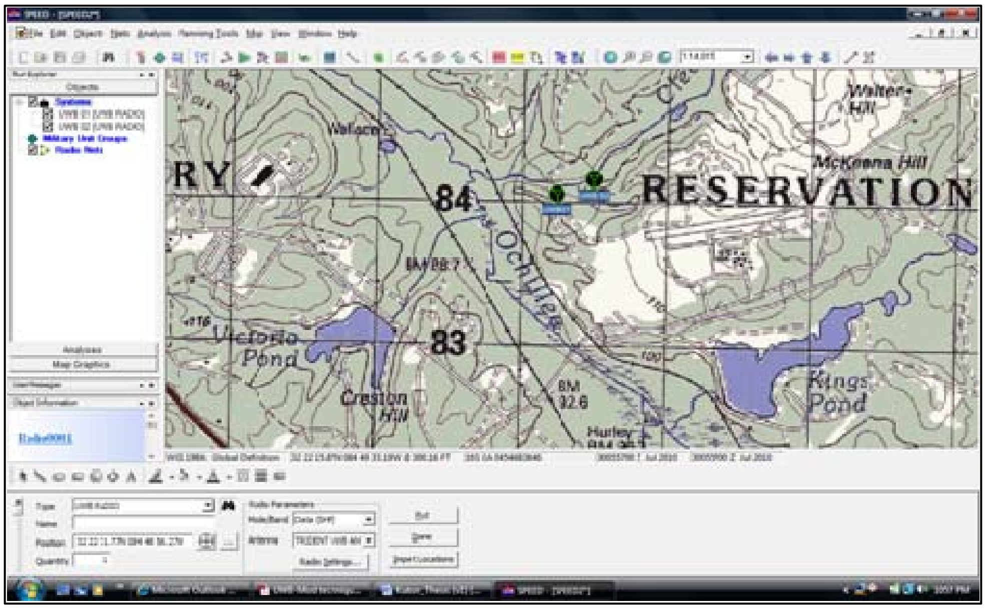

Figure 28. UWB radio emplacement for PTP simulation

2. 802.11n Radio System

The PTP arrangement for the 802.11n radios is exactly the same as the UWB radio system. All 802.11n radio parameters established in the previous section are used in this analysis. One radio, 802.11n 02, has a total antenna height of 8 inches to simulate ground emplacement while the other radio, 802.11n 01, is set at 3 feet to simulate being mounted at a static position near the clearing in the tree line. The range ring around 802.11n 01 is placed at 300 meters and is used to gauge placement distance. Both 802.11n radios will be initially placed 300 meters apart for one another. If the radios fail to achieve the desired received signal strength, 802.11n 02 will be moved closer to

802.11n 01 until the threshold is established. The desired receiver signal strength threshold for a 9 Mbps data rate, BPSK, and convolutional 3/4 coding scheme will be around -85 dBm with a 8-10 dB SNR [Carpenter & Barrett, 2008]. The TLM 1:50,000 map is again used as reference for elevation and vegetation data for this PTP simulation.

3. 802.16e Radio System

The PTP arrangement for the 802.16e is also exactly the same as the UWB and 802.11n radio system. All 802.16e radio parameters established in the previous section are used in this analysis. One radio, 802.16e 02, has a total antenna height of 8 inches to simulate ground emplacement while the other radio, 802.16e 01, is set at 3 feet to simulate being vehicle mounted at the edge of the tree line. Power will be initially established at 250 mW. If the radios fail to achieve the desired received signal strength, the power will be incrementally increased instead of moving the radios closer together. This dynamic capability will be increased in increments of 25 mW until connectivity is achieved. If the received signal strength threshold is never achieved and maximum power capacity is reached, the radio will then be moved physically closer until it is achieved. The desired receiver signal strength thresholds for a 8 Mbps data rate, 16-QAM, and convolutional 1/2 coding scheme will be around -78 dBm with a 16 dB SNR [Tessco, 2007]. The TLM 1:50,000 map is used as reference for elevation and vegetation data for this RCA simulation.

D. SIMULATION RESULTS

1. UWB Radio System

The UWB radio system's PTP simulation produced some interesting results once the NLoS attenuation was factored in. All UWB simulations added .65 dB per meter of NLoS attenuation. The UWB 802.11n radio systems were emplaced 300 meters apart and the receiver signal strength was just too low to achieve connectivity. At 300 meters, the receiver signal strength was -271 dBm with a -150 dBm predicted SNR. Radio 02 was moved 100 meters close to radio 01 to attempt to establish connectivity. At 200

meters, the UWB radio system produced better results but still failed to achieve the desired receiver sensitivity for the desired 54 Mbps data rate. The radio systems produced receiver signal strengths of -200 dBm with a -78 dBm predicted SNR. This lack of connectivity continued until the UWB radio systems were moved 35 meters apart. At 35 meters, the radio systems successfully established the receiver sensitivity to achieve 54 Mbps data rates utilizing QPSK with convolutional 1/3 coding scheme. The results before calculating NLoS attenuation are displayed in Figure 29. The radio systems produced a receiver signal strength of -71 dBm with 8 dB predicted SNR. If additional dBm is required for the fade margin, the radio could be moved 5 meters close to achieve around 5 dB to help with the reliability of the wireless connection.

DTED Level: DTED Level 1 | Analysis Interval: 30.0m (FINE) | Datum: WGS 1984: Global Definition

Link Name: PTP Link 0001 | Overall Link Status: Acceptable | Link Type: Digital

Left Radio		Right Radio	
Radio Name:	UWB 01	Radio Name:	UWB 02
Radio Location:	32 22 28.56N 084 49 06.10W 16S GA 0524784051	Radio Location	32 22 28.79N 084 49 04.76W 16S GA 0528184055
Radio Type:	UWB RADIO	Radio Type:	UWB RADIO
Transceiver Name:	UWB	Transceiver Name:	UWB
Mode:	Data	Mode:	Data
Band:	SHF	Band:	SHF
Transmit Power:	0.050000 W	Transmit Power:	0.050000 W
Transmit Frequency:	3000.000000 MHz	Transmit Frequency:	3000.000000 MHz
Emission Designator:	DATA	Emission Designator:	DATA
Modulation:	QPSK	Modulation:	QPSK
Coding Scheme:	Convolutional 1/2	Coding Scheme:	Convolutional 1/2
Antenna Type:	TRIDENT UWB ANT	Antenna Type:	TRIDENT UWB ANT
Desired Margin:	0.000000 dB	Desired Margin:	0.000000 dB
Received Sig Lvl:	-46.304405 dBm	Received Sig Lvl:	-46.304405 dBm
Path Clearance:	0.93 FT	Path Clearance:	0.93 FT
Scatter Angle:	0.000000 deg	Scatter Angle:	0.000000 deg
Data Rate:	53000.000000 Kbps	Data Rate:	53000.000000 Kbps
Reliability:	N/A %	Reliability:	N/A %
Multipath Spread:	N/A ns	Multipath Spread:	N/A ns
Calc. Data Rate:	N/A	Calc. Data Rate:	N/A
Calc. Required Power:	N/A	Calc. Required Power:	N/A
Analog Link Status (R to L):	Acceptable	Analog Link Status (L to R):	Acceptable
Digital Link Status (R to L):	Acceptable	Digital Link Status (L to R):	Acceptable
Predicted S/N:	76.248405 dB	Predicted S/N:	76.248405 dB
Excess Margin:	55.248405 dB	Excess Margin:	55.248405 dB
Calc. Theoretical BER:	2.021e-311	Calc. Theoretical BER:	2.021e-311
Eb/No:	53.286809 dB	Eb/No:	53.286809 dB
Calc. C/kT:	133.539868 dBHz	Calc. C/kT:	133.539868 dBHz
Calc C/N:	56.297109 dB	Calc C/N:	56.297109 dB

Figure 29. UWB PTP analysis results before NloS calculation

2. 802.11n Radio System

The 802.11n radio system's PTP simulation also provided some understanding on how this radio system will perform in an austere environment. All 802.11n simulations

added .5 dB per meter of NLoS attenuation. The 802.11n radio systems were emplaced 300 meters apart and the receiver signal strength and SNR were too low to even achieve a 1 Mbps data rate using BPSK. At 300 meters, the receiver signal strength was -210 dBm with a -112 dBm predicted SNR. Radio 02 was moved 100 meters close to radio 01 to attempt to establish connectivity. At 200 meters, the 802.11n radio system produced better results but still failed to achieve the desired receiver sensitivity for the desired 9 Mbps data rate. The radio systems produced receiver signal strengths of -150 dBm with a -52 dBm predicted SNR. The radios were again moved 100 meters closer in an attempt to establish connectivity. At 100 meters, the radio systems successfully established the receiver sensitivity to achieve 9 Mbps data rates utilizing BPSK with convolutional 3/4 coding scheme. The results before calculating NLoS attenuation are displayed in Figure 30. The radio systems produced receiver signal strengths of -81 dBm with a 17 dBm predicted SNR. The additional 4 dBm will be applied to the fade margin to help with the reliability of the wireless connection. In comparison to the UWB radio system, 802.11n radio system was able to achieve this same data rate in 75 meters. Overall, the 802.11n radio's received signal strength was greater than the UWB radio system but this system used more power and a focused beam pattern.

DTED Level:	DTED Level 1	**Analysis Interval:**	30.0m (FINE)	**Datum:**	WGS 1984: Global Definition		
Link Name:	PTP Link 0002		**Overall Link Status:**	Acceptable		**Link Type:**	Digital

Left Radio		Right Radio	
Radio Name:	802.11n 01	**Radio Name:**	802.11n 02
Radio Location:	32 22 28.39N 084 49 06.70W 16S GA 0523184046	**Radio Location**	32 22 29.45N 084 49 03.52W 16S GA 0531484080
Radio Type:	SILVUS SC2000	**Radio Type:**	SILVUS SC2000
Transceiver Name:	802.11n	**Transceiver Name:**	802.11n
Mode:	Data	**Mode:**	Data
Band:	UHF	**Band:**	UHF
Transmit Power:	1.000000 W	**Transmit Power:**	1.000000 W
Transmit Frequency:	2412.000000 MHz	**Transmit Frequency:**	2412.000000 MHz
Emission Designator:	20MHZ	**Emission Designator:**	20MHZ
Modulation:	QPSK	**Modulation:**	QPSK
Coding Scheme:	Convolutional 1/2	**Coding Scheme:**	Convolutional 1/2
Antenna Type:	WAVES PLANAR ARRAY 1	**Antenna Type:**	WAVES PLANAR ARRAY 1
Desired Margin:	0.000000 dB	**Desired Margin:**	0.000000 dB
Received Sig Lvl:	-31.122398 dBm	**Received Sig Lvl:**	-31.122398 dBm
Path Clearance:	3.17 FT	**Path Clearance:**	3.17 FT
Scatter Angle:	0.000000 deg	**Scatter Angle:**	0.000000 deg
Data Rate:	12000.000000 Kbps	**Data Rate:**	12000.000000 Kbps
Reliability:	N/A %	**Reliability:**	N/A %
Multipath Spread:	N/A ns	**Multipath Spread:**	N/A ns
Calc. Data Rate:	N/A	**Calc. Data Rate:**	N/A
Calc. Required Power:	N/A	**Calc. Required Power:**	N/A
Analog Link Status (R to L):	Acceptable	**Analog Link Status (L to R):**	Acceptable
Digital Link Status (R to L):	Acceptable	**Digital Link Status (L to R):**	Acceptable
Predicted S/N:	67.238525 dB	**Predicted S/N:**	67.238525 dB
Excess Margin:	42.238525 dB	**Excess Margin:**	42.238525 dB
Calc. Theoretical BER:	4.047e-312	**Calc. Theoretical BER:**	4.047e-312
Eb/No:	67.256318 dB	**Eb/No:**	67.256318 dB
Calc. C/kT:	141.058430 dBHz	**Calc. C/kT:**	141.058430 dBHz
Calc C/N:	70.266617 dB	**Calc C/N:**	70.266617 dB

Figure 30. 802.11n PTP analysis results before NLoS calculation

3. 802.16e Radio System

The 802.16e radio system's PTP simulation provided some more understanding with MIMO capable radio systems in this environment. All 802.16e simulations added 1 dB per meter of NLoS attenuation. The 802.16e radio systems were emplaced 300 meters apart and the transmit power was initially set at 250 mW and increased to 2 W without achieving the receiver signal strength and SNR required to attain a 8 Mbps data rate. Additionally, the receiver signal strength and SNR were too low to also achieve the 2 Mbps data rate using BPSK. At 300 meters, the receiver signal strength was -353 dBm with a -252 dBm predicted SNR. Radio 02 was moved 100 meters close to radio 01 to attempt to establish connectivity. At 200 meters, the 802.16e radio system produced better results but still failed to achieve the desired receiver sensitivity for the desired 8 Mbps data rate. The radio systems produced receiver signal strengths of -240 dBm with a -139 dBm predicted SNR. The radios were again moved 100 meters closer in an attempt

to establish connectivity. At 100 meters, the radio still failed to achieve the desired receiver signal strength and SNR. The 802.16e radio systems produced receiver signal strengths of -133 dBm with a -25 dBm predicted SNR. The radios were moved again. This time the radios were spaced 50 meters apart and the radio systems successfully connected. At 50 meters, the 802.16e radio systems established the receiver sensitivity to achieve 9 Mbps data rates utilizing 16-QAM with convolutional 1/2 coding scheme. The results before calculating NLoS attenuation are displayed in Figure 31. The radio systems produced a receiver signal strength of -78 dBm with a 23 dBm predicted SNR. The radio could be separated to 60 meters and achieve a 4 Mbps data rate with QPSK and the convolutional 1/2 coding scheme because the receiver signal strength was -88 dBm with 12 dBm of SNR [Araújo, n.d.]. Overall, the 802.16e radios received signal strength was greater than the 802.11n radio system; however, this use of a 5 GHz frequency increased the NLoS and natural attenuation the 802.16e radios needed to surpass 802.11n's capabilities.

DTED Level: DTED Level 1 Analysis Interval: 30.0m (FINE) Datum: WGS 1984: Global Definition
Link Name: PTP Link 0003 Overall Link Status: Acceptable Link Type: Digital

Left Radio		Right Radio	
Radio Name:	802.16e 01	Radio Name:	802.16e 02
Radio Location:	32 22 28.89N 084 49 06.30W 16S GA 0524184061	Radio Location	32 22 29.27N 084 49 04.47W 16S GA 0528984074
Radio Type:	WIMAX RADIO	Radio Type:	WIMAX RADIO
Transceiver Name:	802.16	Transceiver Name:	802.16
Mode:	Data	Mode:	Data
Band:	SHF	Band:	SHF
Transmit Power:	2000.000000 mW	Transmit Power:	2000.000000 mW
Transmit Frequency:	5725.000000 MHz	Transmit Frequency:	5725.000000 MHz
Emission Designator:	OS SPECTRA	Emission Designator:	OS SPECTRA
Modulation:	16QAM	Modulation:	16QAM
Coding Scheme:	Convolutional 1/2	Coding Scheme:	Convolutional 1/2
Antenna Type:	FORMING I (PHASED ARRAY	Antenna Type:	FORMING I (PHASED ARRAY
Desired Margin:	0.000000 dB	Desired Margin:	0.000000 dB
Received Sig Lvl:	-28.450103 dBm	Received Sig Lvl:	-28.450103 dBm
Path Clearance:	1.36 FT	Path Clearance:	1.36 FT
Scatter Angle:	0.000000 deg	Scatter Angle:	0.000000 deg
Data Rate:	9000.000000 Kbps	Data Rate:	9000.000000 Kbps
Reliability:	N/A %	Reliability:	N/A %
Multipath Spread:	N/A ns	Multipath Spread:	N/A ns
Calc. Data Rate:	N/A	Calc. Data Rate:	N/A
Calc. Required Power:	N/A	Calc. Required Power:	N/A
Analog Link Status (R to L):	Acceptable	Analog Link Status (L to R):	Acceptable
Digital Link Status (R to L):	Acceptable	Digital Link Status (L to R):	Acceptable
Predicted S/N:	71.387581 dB	Predicted S/N:	71.387581 dB
Excess Margin:	50.387581 dB	Excess Margin:	50.387581 dB
Calc. Theoretical BER:	4.872e-312	Calc. Theoretical BER:	4.872e-312
Eb/No:	69.624077 dB	Eb/No:	69.624077 dB
Calc. C/kT:	142.176802 dBHz	Calc. C/kT:	142.176802 dBHz
Calc C/N:	72.634377 dB	Calc C/N:	72.634377 dB

Figure 31. 802.16e PTP analysis results before NLoS calculation

E. SUMMARY

This chapter captured data on how wireless penetration technologies will perform in a triple canopy environment. A GOTS modeling application, SPEED, served as the evaluation tool. The details of the GOTS simulation was captured through the modeling objectives, model and simulation development, and model results for several different UWB and MIMO technologies. Modeling applications are not perfect, and this chapter provided an excellent example. SPEED did not account for the NLoS attenuation due to trees and thick foliage in an austere environment. This required manual computation of this attenuation loss into each radio's received signal strength and SNR. All three radio technologies seem like viable candidates for extending the tactical network in austere environment. In comparison, the UWB radio transmitted a fraction of the power of the MIMO radios and achieved some very favorable data rates; however, the distance was limited to around 40 meters. These same data rates were achieved with the 802.11n radio; however, the distances were significantly increased by twice as much. In the end, this simulation was not able to produce a radio system capable of extending the tactical network beyond 100 meters with the data rates required to support greater than a company-level unit.

One additional concern was the inability of the simulation to produce data to properly evaluate the data throughput and reliability of these technologies in this environment. Thus, a future experiment in an actual austere environment would be beneficial for each type of technology discussed in this chapter. The simulation results, taken as a whole, provides the insight for UWB and MIMO application and implementation into the tactical network discussed in Chapter V and permits the development of a future testing plan discussed in Chapter VI.

V. IMPLEMENTATION AND APPLICATION INTO THE TACTICAL NETWORK

A. INTRODUCTION

In this chapter, the implementation and application of MIMO and UWB technologies into a tactical network for triple canopy environments will be discussed. This chapter will focus on the requirements to build a stable and robust network that can be used to achieve net-centricity. This chapter applies the data collected in Chapter IV and develops a vision for deploying UWB and MIMO technologies in a tactical network to maximize interoperability and availability for units operating in an austere environment. For instance, a properly constructed network should be capable of supporting sensor, voice, video, position location, chat, and imagery capabilities across a network. Ultimately, this chapter will propose a model and discuss some requirements for achieving an integrated network capable of supporting multiple functions during NCW. It should be noted that the scope of this model focuses on a small-scaled tactical network; therefore, this tactical network would require more detailed research with the network layer (layer 3) and higher of the seven-layer Open Systems Interconnection (OSI) model.

B. PROPOSED UWB/MIMO IMPLEMENTATION

1. Network Implementation/Application Model

The conceptual UWB/MIMO tactical network model, illustrated in Figure 32, serves as a vision for implementing and applying different penetrating technologies in a triple canopy environment. This model takes a holistic approach for providing possible solutions when dealing with signal propagation that were defined in Chapter II and observed in Chapter IV. Both UWB and MIMO technologies are capable of providing adequate service in this environment, so the goal of this conceptual model is to develop a network architecture that is capable of closing existing network gaps for this type of environment.

Operationally, the data will flow throughout the conceptual model starting with the clustered sensor nodes, depicted in yellow. Once these sensors are activated and have data to send, the node(s) will transmit their data via UWB or MIMO radios out of the triple-canopy foliage to areas along the riverbank that have clear LoS. This clear LoS will allow for satellites, SURCs, or UAVs to relay or retrieve the sensor's data and forward to the TOC. Once in the TOC, data can be shared with external agencies via the GIG. Communication devices will operate under this same premise but will be depend on the QoS of the network. Overall, this is a broad overview, and we need to further consider several implementation factors which are discussed later.

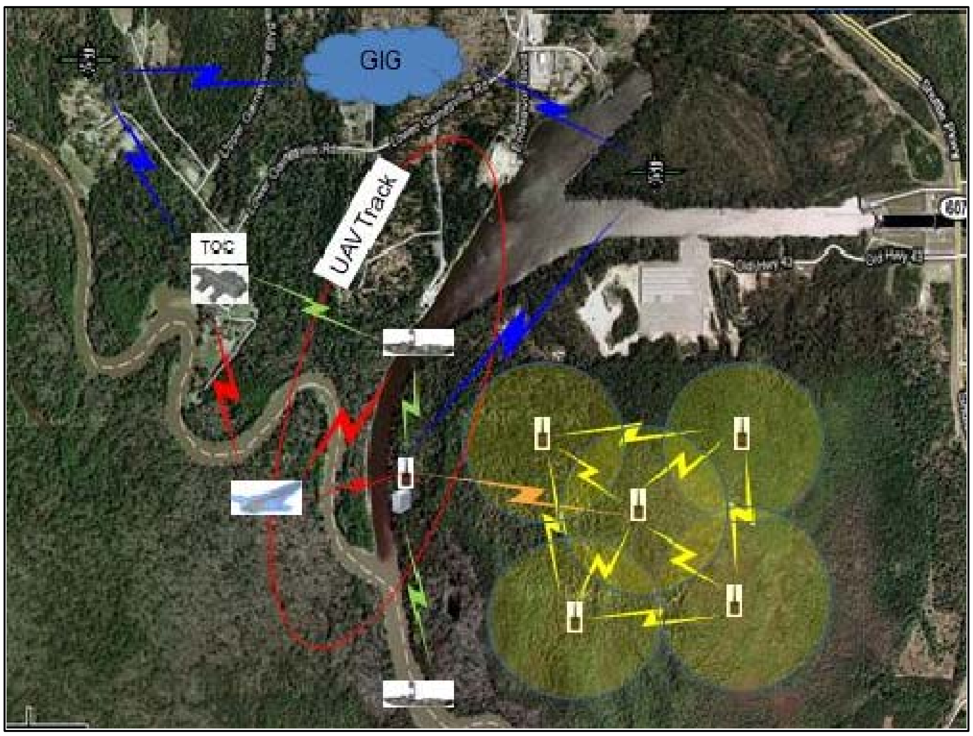

Figure 32. Conceptual UWB/MIMO tactical network model

2. Emplacing UWB/MIMO Technologies

Sensor nodes will need to be emplaced with the intent of providing sufficient overlapping coverage for other sensors while ensuring network connectivity. This will limit sensor coverage areas unless the network is extended utilizing certain wireless

protocols. In the conceptual model, network connectivity is extended by utilizing wireless mesh protocol to "talk" to each other in order to share the network connection in this thick vegetation and dense woods. This "talking" is an advantage for a mesh network because each radio or sensor node acts as a retransmission site; therefore, the size of the mesh network is directly dependent on the number of nodes utilized within this mesh cluster. The area of network coverage will increase as the number on sensor nodes increase and are spread out throughout the larger area. Even with this extension ability, the physical constraints for UWB and MIMO technologies will also need to be considered. These will be discussed in the scalability section later in this chapter.

Finally, dynamic routing needs to be established in this mesh cluster network. This will ensure sentry nodes automatically choose the quickest and safest path to route data through the network and back to the TOC. This offers the greatest advantages for communication devices operating in a triple-canopy environment. For example, communication devices utilizing UWB and MIMO technologies are mostly mobile; therefore, if one communication device drops out of the network, due to hardware failure or any other reason, other neighboring communication devices will find another route by using this routing protocol.

3. Timeliness and Latency of Data

Timeliness and latency of data also need to be considered for the tactical network. The conceptual model assumes the TOC requires real-time data in order to gain quicker Situational Awareness (SA) than an adversary; therefore, redundancy was established to ensure network reliability and robustness. As discussed earlier, the senor data or voice communication would be routed through the SURCs that are patrolling the river, collected at static retrains site on the river bank then relayed through a UAV, or routed via satellite. However, all of these requirements might not be needed or may be restricted based on service needs. The Commander in the TOC needs to determine the importance and timeliness of the data because this will lay the foundation for establishing effective service needs. For example, if the TOC information systems have a toleration of one minute, several MBs of sensor data could be collected at the river bank and uploaded by a

UAV loitering in the southeastern portion of the UAV track. Once the UAV establishes a link in the northeastern portion of the track, it could then download the data to the TOC. The employment of such platforms will require equivalent throughput capabilities that were generated by the PUMA system discussed in Chapter III.

If VOIP communications or video surveillance systems are going to be utilized, the commander will need to ensure UWB or MIMO technologies are capable of providing adequate bandwidth and establishing an effective QoS scheme that will ensure the lowest latency possible. This is all contingent on the size of the unit(s) operating within an area. For example, a platoon-size unit may require connectivity for: tracking the locations and status of every Soldier or Marine on the Platoon Commander's ruggedized laptop, streaming video from every Soldier or Marine's helmet cameras, and communicating to higher over VOIP will require an extensive amount of bandwidth. Fulfilling all of these applications will possibly produce bottlenecks that prevent communication and data from filling the network "pipe". MIMO technologies have a higher possibilities of not fulfilling these services without degrading the network and increasing latency. At the end of the day, this environment naturally produces higher latency so the key will be to develop an efficient QoS scheme to lower latency as much as possible.

4. Scalability for Platform Requirements

When addressing the different platforms in the conceptual model, several scalability requirements need to be met before voice and data communications would be available for during NCO. The first requirement is developing connectivity for sensors and dismounted warfighters within this environment. The second requirement is providing radio systems for vehicle and watercraft platforms. The third involves developing UAV radio platforms.

When looking at developing connectivity for sensors and dismounted troops, the range of UWB and MIMO technologies need consideration. If a mesh network was developed based on the data from the experiment in Chapter IV, UWB technologies will require a larger number of nodes due to transmission range capabilities, while MIMO

technologies allow for greater dispersion and distance between nodes. For example, when emplacing UWB sensors, they will require a larger number of nodes since UWB sensors will be limited to less than 40 meters. This will increase the cost of implementation, but allow for greater throughput in this specific venue.

Also, the size of the radios must be considered. The warfighter is already burdened with an extensive payload to carry; therefore, their communications devices will need to lightweight and small. For example, the radio system needs to be mounted on a tactical vest or patrol pack, as depicted in Figure 33. Legacy radio systems used in conjunction with a small device interface appears the most beneficial way of achieving connectivity. For sensors, the desired application will be a small detectable footprint while providing extensive working durations once emplaced. In either situation, the application will produce additional considerations for power sourcing. UWB technologies provide the most optimal solution for these applications since the radio system needs to minimize power consumption while allowing for extensive use. As for security, both MIMO and UWB technologies afford sensors and dismounted warfighters some level of security; however the greatest LPI/LPD would be obtained using UWB technologies. By maintaining this benefit, friendly forces will be able to achieve the element of surprise and allow for the greatest gathering of critical intelligence. In all cases, UWB technologies arguably provide the greatest advantage in fulfilling this first requirement if sensors and dismounted troops will be deployed for an extensive amount of time.

The second requirement is providing the radio systems for watercraft and vehicle platforms. Both of these platforms are capable of hauling larger radio systems; therefore, some of the first requirement concerns are not applicable here. For example, battery consumption with vehicle and watercraft mounted radio systems are less of a concern since they will be powered from the vehicle and watercraft batteries or generators. This benefits MIMO systems especially with the long range transmission capabilities. Also, antenna configuration is not as much of a concern since antennas can be mounted on the watercraft or vehicle and can be easily erected, aimed, and stabilized. The watercraft and vehicle mounted systems provides and extension and redundancy for the tactical network

if necessary. For this second requirement, LPI/LPD still plays an important factor. As for this requirement, both technologies can provide adequate support of the tactical network; however, MIMO technologies better fulfill the long-haul expectations from vehicle and watercraft utilization.

The third requirement involves the employment of radios on an aerial platform such as an Unmanned Aerial Vehicle (UAV) or manned aircraft. The use of a UAV would greatly extend network connectivity across NLoS conditions that are faced in a triple canopy environment. Since the UAV would be utilized as a collector or relay, it will require fast upload and download capabilities for shorter loitering time. In Chapter III, PUMA's UWB capability was more than adequate when deployed on a Raven UAV loitering at 1000ft AGL. However, MIMO capabilities would debatably provide similar results. The only attribute the UWB technology has over MIMO is it typically can produces a smaller, lighter radio system. Therefore, it is the size of the UAV or aerial platform and payload capability that will dictate which system to best suited for employment.

C. INTEGRATING UWB AND MIMO SYSTEMS INTO THE TACTICAL NETWORK

Integration issues will arise from the conceptual model so the successful integration of UWB and MIMO technologies into a tactical network topology will require solving some common interoperability problems, but we can leverage current integration techniques utilized for the integration of previous military information systems. For the most part, previous military-procured network systems have been "stovepipe" solutions for accomplishing service-specific missions. These systems are isolated and are not capable of integrating with each other or into the network. This is a concern since all of the information gathered from sensors will need to be shared across tactical networks or the GIG in order to truly exploit NCO. Also, the network topology will need to provide connectivity for every node in order to coordinate movements and build Situational Awareness (SA) within a commander's Area of Responsibilities (AORs). This will require every node being on one network.

In many instances, the underlying concern is dealing with proprietary sensor or communication systems. For instance, Single Channel Ground and Airborne Radio System (SINCGARS) military radio platforms cannot be incorporated into a network to share battlefield information. This problem can be arguably solved with the evolution of Internet Protocol (IP)-based technology, such as IP-based end systems or IP-based interfaces, to provide a gateway for single channel radio platforms conversion. Recently, the DoD has been tackling these network integration issues, and the utilization of several different IP-based interfaces will provide a piece the puzzle for achieving overall connectivity within this tactical network. With certain contractual modifications to these interfaces, these devices will arguably allow for integration of UWB or MIMO technologies into the tactical network and provide the accessibility and reliability required to conduct NCOs in a triple canopy environment.

1. CenGen's Network Interface

CenGen's device interface was one of the network solutions utilized for several different communication and sensor platforms during recent field testing conduct in Virginia Beach, VA. These specific Device Interface Units (DIUs) were designed to be utilized in conjunction with WaveRelay's 802.11a OFDM Mesh Network; however, modification or new prototype development is possible. One key consideration for any type of DUI is it must operate and support in the rigorous, all-weather triple canopy environment by Soldiers or Marines. CenGen's DIU offers a solution. As depicted in Figure 33, each DIU is a compact, rugged IP-based interface designed for harsh environments that provides support for a single device requiring radio or data transmission. CenGen's compact DIU offers a uniquely capable tactical network integration solution that is ideally suited to deploy in austere environments where size, weight and energy considerations are important, such as the case for triple canopy surroundings. Ideally, CenGen's NIU requires minimal operator training, is capable of rapid set-up, and supports mobile warfighters.

Figure 33. CenGen’s DIU and shown mounted on a tactical vest

CenGen’s DIU also provided the gateway that enabled analog video to be streamed from the sensor camera ball to the TOC several miles away over the 802.11a mesh infrastructure. As illustrated in Figure 34, the RCA cables were connected from the sensor camera ball system into the DIU, and this allowed for the analog video being displayed on the handheld monitor to be integrated. Each DIU is able to support several different types of connections; however, it is only limited to one sensor or communication device. The DIU provided a seamless interface between radios, sensors, or other communication assets using IP-based technology. The DIU could be used as a standalone interface or as part of a larger system. Over the course of the observed exercise, the DIU supported tactical functions such as: sensor alerts, video streaming, GPS tracking, Voice over Internet Protocol (VoIP), and Internet Relay Chat (IRC) for squad-size units.

Figure 34. Analog sensor and DIU integrated with vehicle WaveRelay system

2. Trident's Radio Network Interface Controller (RNIC)

As briefly discussed in Chapter III, Trident's Radio Network Interface Controller (RNIC) is another interface that can be carried by the warfighter. The RNIC provides the capability for the warfighter to communicate and pass messages and text by integrating existing military radios into Trident's UWB Mesh Network. As shown in Figure 35, the RNIC is very compact (3 inches x 4 inches) and weighs around 1.2 lbs with AA batteries included. It too was designed to withstand harsh conditions in austere environments. It has a watertight, ruggedized housing, but the most attractive feature is the RNIC's ability to interoperate with acquired military radios. The RNIC is interoperable with the PRC-148, PSC-5D, SINCGARS (C,F), PRC-150, and PRC-117 [Trident Systems, 2008]. Hence, UWB mesh technology is currently capable of providing any size unit on-demand radio connectivity while minimizing their RF footprint on the battlefield. Also, the RNIC has a max baud rate of 16kbps utilizing military radios or greater than 100kpbs utilizing IEEE standards.

Figure 35. Trident's RNIC [from: Trident Systems, 2008]

3. Raytheon's Mobile Ad hoc Interoperability Network Gateway (MAINGATE) System

Raytheon's MAINGATE system is a radio system that serves as an IP-based gateway to translate different radios' signals into message packets, which will permit linking different systems together. Again, this system provides solutions to current interoperability issues with disparate military radio system. MAINGATE is a prototype radio that uses a mobile ad hoc networking capability to link devices via IP-based transmissions. The MAINGATE system uses MIMO technologies; therefore, reliability issues such as signal loss and interference are mitigated with the use of this technology and Mobile Ad Hoc Networking (MANET) protocols [Kenyon, 2009]. As discussed with the Hydra System in Chapter III, this system has the capability of providing tactical, real-time, high-fidelity video, data, and voice services to support tactical operations in either maneuver or dismounted operations. MAINGATE allows a unit's vehicles to serve as individual communications nodes for their portable squad radios and other digital and analog equipment. This system can also be installed in larger unmanned aerial systems that can handle the payload. Utilizing MIMO technologies, it will provide NLoS connectivity or transmit messages via a satellite communications terminal up to Iridium or Mobile Star satellites. The MAINGATE system, as illustrated in Figure 36, is larger than the previous interfaces; therefore, this gateway system needs to be vehicle or boat

mounted. It has eight ports for linking systems into the network. Three ports are for analog radios, three are digital radios, and two MANET channels. All of which can run simultaneously [Kenyon, 2009].

Figure 36. Raytheon's MAINGATE System [from: Kenyon, 2009]

D. DEVELOPING A COMMON OPERATING PICTURE

In the conceptual model, the TOC needs to develop a Common Operational Picture (COP) in order to support NCOs and operations in a commander's AOR. The COP is a tool utilized by military leaders to share relative battlefield information in order to build SA. For example, the data collected and transmitted from nodes will be available for all other nodes in the AOR. This data could be information on friendly or hostile land and sea positions, most recent intelligence from sensors, or any other information a higher command deems vital for success of the mission. As discussed in the integration section of this chapter, this data is provided through UWB and MIMO radios coupled with a device interface, if required. As a result, the UWB and MIMO radios will ensure data is quickly and continually delivered for the TOC to maintain a combined near-real time and interconnected picture of the AOR.

The data for the COP is collaborated through a variety of commercial off-the-shelf (COTS) or GOTS mapping applications. These COTS or GOTS mapping applications serve as the foundation. For example, Falconview, depicted in Figure 40, is a GOTS mapping application and you can see the different types of information being

fused together from multiple sources to form a COP. Any node connected into the network has the capability of receiving this information. For example, the Mobile Foot Patrol (MFP) and TOC will both be able to view the live video feed in order to simultaneously build SA. Also, all nodes are able to maintain real-time SA with the TOC via mIRC. This fusion will be achieved through a common programming language and interfaces.

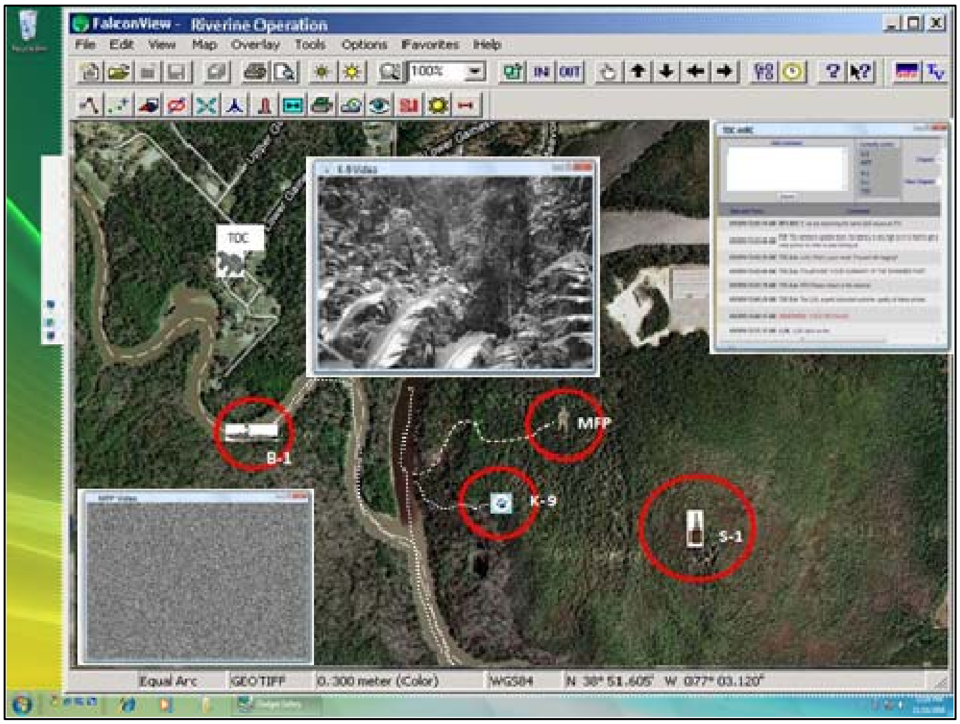

Figure 37. Conceptual COP for Austere Environment using Falconview

1. Application Program Interfaces

GOTS or COTS mapping application will need to consider which Application Program Interfaces (APIs) are associated with the software program. An API is the interface between an application and the underlying platform services which will enable access to these services in the tactical network. An API specifies the mapping between program syntax and the features of a specific service, and thereby provides access to that service from applications written in a particular programming language. For example, APIs are used to request the services of components such as directories, file transfers, e-

mail, and remote database access. Developing a COP utilizing COTS mapping applications may be easier to acquire for quicker implementation, but will limit application services if the proper APIs are not already provided or future development of required APIs are not planned. GOTS systems have these same restrictions; however, some GOTS systems have greater flexibility on developing and adding more APIs when new sensor or communication systems are developed. During recent governmental field exercises, different vendors wrote code for their APIs and computer programmers dropped their API programs into the directory for the GOTS system. Then, the sensors showed up in the COP system as a plug-in. Again, depending on how you want to get your data into the system, the plug-in will facilitate that transfer of data. This is arguably the best method for achieving NCO in the tactical network—document and certify all standards-based APIs through some type of enterprise programming process and incorporate in a future revision of the COP, if necessary.

2. Developing Common Protocols for Data Integration

As stated earlier, the integration of data is required to achieve a robust COP within the tactical network. Hence, common protocols and representation requirements will need to be developed in order to exchange the information that UWB and MIMO radios are transmitting. One of the most commonly used methods for exchanging data or storing information is utilizing a tag-based programming language called the eXtensible Markup Language (XML). XML's tags identify different pieces of information and structure data to provide meaningful representation into the COP [McFarland, 2009]. The beauty of XML is that it is not really a markup language like Hyper Text Markup Language (HTML) and it allows for the creation of vendors to generate creative tags so long as they follow a set of guidelines. It is important to understand that XML is not a replacement for HTML. In most web applications, XML is used to transport data, while HTML is used to format and display the data. In other words, vendors can extend the language to fit their needs so the overall ontology still meets higher guidelines. Another favorable factor is XML allows an unlimited number of tags to be associated with the

information. In other words, an unlimited number of tags can be used as meta-data. This provides the opportunity for a greater amount of information available for a COP, if desired.

Figure 41 provides an example of how XML applies for tag integration. If you wanted to provide data from a specific node into another messaging infrastructure, this is a basic explanation on how to accomplish this. Essentially, the new <cntx> tag is injected into the message structure at the <detail> tag level to encapsulate the nodes data. The <cntx> tag has at least two attributes to describe the platform (UAV, SURC, K-9, FMP, etc) and mode of operation (task, sensor, video, status) for each platform. The identifier attribute (path following, link control, etc.) is an optional parameter.


```xml
<?xml version="1.0" standalone="yes"?>
<event version="2.0" uid="K-9 Video" type="a-f-.-.-."
time="2006-05-25T22:38:32.18Z" start="2006-05-25T22:38:32.18Z" stale="2006-05-
25T22:40:32.18Z" how="m-g" qos="0-r-c">
<detail>
<cntx platform=”K-9” mode=”task” identifier=”HRI”>
<parameters heading=”230” />
<camera cameratype=”video” zoom=”15” />
<attempts>3</attempts>
<timeout></timeout>
<originatorID>36</originatorID>
</cntx>
</detail>
<point lat="36.73357" lon="-120.77661" hae="500" le="10" ce="10" />
</event>
```


Figure 38. Example of XML and tag integration

E. NETWORK MANAGEMENT

Whether a conceptual model or actual tactical network, network management will be vital once any tactical network is established. This management of the UWB or MIMO devices on the tactical network will require some type of network management software for monitoring efficient functionality for these network nodes and maintaining the network’s overall health.

1. Network Management Software

In a tactical network with many UWB or MIMO nodes, problems are bound to arise that the users cannot repair on their own. Network management software will have the ability to query these nodes on the network for specific information. Information about connection status, packet loss, throughput, etc., can be gathered from the network nodes where this information is utilized to make management decisions. This will provide network managers the ability to remotely restore the nodes so that the warfighter can focus on their mission or help determine solutions for network bottlenecks developed by overloading sensor information. The system also needs to be capable of autonomously monitoring when sensor nodes or other nodes have problems. Since nearly all of these management concerns can be remotely handled, the network management system should be located within the TOC. This should be no lower than company-level or command centers that maintain a semi-static position.

2. Simple Network Management Protocols (SNMPs) and Management Information Bases (MIBs)

From a network management perspective, the establishment of a network with all enabled Simple Network Management Protocol (SNMP) devices is desired. SNMP forms part of the IP suite as defined by the Internet Engineering Task Force (IETF). SNMP is used by network management systems to monitor network attached devices for conditions that warrant administrative attention in order to provide the user the required QoS [Subramanian, 2000]. It consists of a set of standards for network management, including application layer protocols. After all, the average human end-user seems only concerned with the availability and responsiveness on an application despite all the technically sophisticated ways in which networking and system resources can be measured. In order to accomplish this, Management Information Bases (MIBs) will need to be utilized.

MIBs specify the management data of a device subsystem, using a hierarchical namespace containing object identifiers. The MIB hierarchy can be depicted as a tree with a nameless root, the levels of which are assigned by different organizations. The

top-level MIB object IDs belong to different standards organizations, while lower-level object IDs are allocated by associated organizations. This structure permits management across the application layer for such user applications as databases, e-mail, video, and biometrics operations. The two most relevant MIBs are: the Application Performance Measurement MIB (RFC 3729), which provides for an end-to-end look at the performance a user experiences from an application on a distributed network by measuring the QoS delivered to end-users by applications and the RTP: A Transport Protocol for Real-Time Applications (RFC3550) that provides for end-to-end network transport functions suitable for applications transmitting real-time data, such as audio, video or simulation data, over multicast or unicast network services [Subramanian, 2000]. With these perspectives, the network manager should get an accurate end-to-end view of the IT infrastructure--the performance of the application, desktop, network, and server, as well as any positive or negative interactions between these components.

3. Proprietary Management Systems

Some proprietary UWB and MIMO radios used in network systems might come with their own network management systems, and this is a concern for tactical networks. By only allowing proprietary management software to be utilized in a tactical network, the ability to effectively manage the availability of applications within the network is severely limited. This increases the dependence on the system's provider—a benefit for the system providers but a hindrance for military units. These contractors will not always be readily available to deploy; therefore, the military unit's network management team will need to use unconventional methods or acquire the proprietary management tools to monitor all components and ensure the tactical network remains operational. Ultimately, the military unit's successful ability to achieve a reliable network will be directly related to the effective usage of the proprietary software to check the traffic load on essential nodes, in order to forecast delays, as well as invoke additional processes that will aid in the ability to handle overloads. These tools can be accessed through a web-based interface that will display information about the system and applications being utilized

within our tactical network or physically available to provide reach-back control and monitor of deployed network sensors. Both are shown below.

Figure 39. WaveRelay's Interface and Trident's Wireless Network Controller (WiNC) [from: Trident Systems, 2008]

F. SUMMARY

In this chapter, the implementation and application of MIMO and UWB technologies into a tactical network for triple canopy environments were discussed. This chapter developed a conceptual model and addressed the requirements for implementing UWB and MIMO technologies in the conceptual model in order to build a stable and robust tactical network capable of achieving net-centricity. As discussed, UWB and MIMO technologies are more than capable of providing for maximum interoperability and availability for units operating in an austere environment, but they need to be successfully integrated. This chapter presented some of these solutions. In addition, the development of the COP provided a generalized framework for fusing the data being transmitted by UWB and MIMO technologies. Finally, the overall management of this network was discussed. All things considered, this conceptual model provides a vision for potential UWB and MIMO technologies and advancing NCW and tactical networks in the future.

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VI. CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

A. CONCLUSION

This thesis focused on the topic of how to extend the tactical network to reach the warfighter operating in triple canopy environments. Triple canopy environments present many interesting RF propagation conditions and dynamic challenges for NCOs. The challenge from a communication perspective is how to bridge the tactical "edge" in an austere environment so military leaders can establish network connectivity for pushing or pulling information to and from warfighters and sensors in order to enhance the COP and establish effective NCOs. This thesis laid the groundwork to bridge the communication challenges by analyzing constraints associated with UWB and MIMO radio technologies in an austere environment, evaluating their effectiveness through simulations, and developing an integration scheme for these technologies to expand the tactical network and bridge the tactical "edge". UWB and MIMO technologies are still in their infancy but this early research and simulation of their abilities looks very promising.

The initial assessment appears that UWB and MIMO technologies have the potential to support at least platoon-sized units. Simulation testing was conducted using the wooded terrain map data near Ft. Benning, Georgia and the results demonstrated that these technologies, at least in a modeled environment, could be used to extend the tactical network in an austere environment. Both MIMO technologies projected 9 Mbps throughput with a nodal dispersion of 100 meters and UWB technologies projected 54 Mbps throughput with nodal dispersion of 35 meters in this environment. Throughput was based on the receiver signal strength, SNR, and specification sheets of each radio tested. For this reason, further testing will need to be conducted to validate the simulation results and capture the actual throughput capability and reliability of these technologies in this environment.

Another assessment appears that interoperability of UWB and MIMO technologies into an existing tactical network is realistic. The conceptual model

identified the requirements for implementing UWB and MIMO technologies in the conceptual model in order to build a stable and robust tactical network capable of achieving net-centricity. The most important requirement was integrating the UWB and MIMO technologies. The thesis touched on the importance of Internet Protocol (IP)-based technology, such as IP-based end systems or IP-based interfaces, to provide a gateway for UWB and MIMO platforms. With certain contractual modifications to these interfaces, these devices will allow for integration of UWB or MIMO technologies into the tactical network and provide the accessibility and reliability required to conduct NCOs in a triple canopy environment. Even though this thesis focused on UWB and MIMO solutions for an austere environment, the requirements identified and solutions provided in Chapter V can apply to communication solutions in all capability sets.

B. ANSWERS TO RESEARCH QUESTIONS

This section discusses the research questions posed for this thesis in Chapter I.

1. Primary Research Question

Given an austere environment with thick vegetation and precipitation, a specified distance between transmitter and receiver, and certain multiple access techniques, how will each wireless radio technology maximize the available bandwidth for the warfighter and extend the tactical edge in the network?

UWB and MIMO radios researched and simulated in this thesis produced similar results for maximizing the available bandwidth for extending the tactical network's "edge". Based on the simulation in Chapter IV, UWB or MIMO radios will adequately facilitate the minimum bandwidth requirements if the throughput requirement is below a 9 Mbps threshold and within the effective range capability of each radio. Keep in mind, further testing will need to be conducted.

In the case of UWB technology, this technology appears to be an ideal physical layer alternative to current wireless communication links. By utilizing millions of time-sequenced narrow pulses over an extremely large spectral mask, UWB is capable of providing very high throughput without the signal interference, multipath fading, high

costs and power requirements associated with other technologies. One of the only drawbacks to UWB is range limitation, and this will require a larger number of nodes in a given area to ensure connectivity. As a result, the cost of implementation will increase.

The 802.11n and 802.16e MIMO technologies do not have such strict range limitations that UWB has since they both are considered narrowband. Theoretically, 802.11n is capable of attaining nearly 600 Mbps utilizing a 4x4 radio system with two streams and a 40 MHz channel. This technology makes it very comparable to UWB. 802.16e, on the other hand, only is capable of providing around 60 Mbps for mobile devices. MIMO techniques will achieve their higher throughput capabilities for an austere environment is different way. MIMO technologies exploit the multipath propagation within an austere environment. This exploitation will ensure the bandwidth requirements for the warfighter are maximized. MIMO's ability to use multiple antennas at the transmitter and receiver improves communication performance—the greater the number of antennas and radios, the greater the throughput. The simulation showed the 802.11n was capable of providing 9 Mbps throughput at 100 meters while 802.16e provide 9 Mbps at 50 meters.

2. Secondary Research Question #1

What is UWB and MIMO technology?

UWB technology utilizes millions of time-sequenced narrow pulses over an extremely large spectral mask. UWB is capable of providing very high throughput without the high costs and power requirements of most wireless technologies and can handle extreme radio propagations associated with an austere environment. Conversely, MIMO technology uses multiple antennas at the transmitter and receiver to improve communication performance. MIMO technology exploits the space dimension and multipath propagation to improve tactical network links in the most demanding and heavily obstructed propagation environments.

3. Secondary Research Question #2

What makes UWB and MIMO technology so effective in an austere environment?

The effectiveness of UWB technology in an austere environment is attributed to its longer wavelength and extremely short pulse durations. Unlike narrowband technology, UWB systems can transmit and penetrate effectively through different materials such as concrete, rocks, trees, or even water. This ability comes at a price—UWB is restricted to lower power requirements and this affects its range capabilities. Additionally, two UWB pulse will not collide since the transmission duty cycle of the UWB pulse is so short and the bandwidth is so wide. This will reduce or mitigate multipath fading and data corruption between tactical nodes within a triple canopy environment.

MIMO technology, on the other hand, thrives off the rich multipath environment associate with an austere environment. MIMO technology leverages this propagation phenomenon by calculating the most optimal switching points based on the level of multipath propagation being received with the MIMO radio. It then dynamically shifts between spatial multiplexing or antenna diversity to offer the necessary coverage or capacity gains demanded from the network at any given time in a triple canopy environment.

4. Secondary Research Question #3

What is the optimal network platform required to properly manage QoS issues to ensure that optimal service is maintained in this network environment?

Developing an optimal network platform to properly maintain QoS issues in this network environment will take time to uncover. There are several levels of network management that will require attention to ensure optimal service. UWB and MIMO nodal placement will be one important issue in integrating UWB and MIMO radios into a mesh network. Nodes will need to be emplaced with the intent of providing sufficient overlapping coverage for other nodes to ensure network connectivity. The size of the mesh network will be directly dependent on the number of nodes utilized within a cluster, so scalability of the network is an important piece of this puzzle. The area of network coverage will increase as the number on sensor nodes increase and are spread out throughout the larger area. Even with this extension ability, the physical constraints for

UWB and MIMO technologies will also need to be considered. UWB technologies will require a larger number of nodes due to transmission range capabilities, while MIMO technologies allow for greater dispersion and distance between nodes. For example, when emplacing UWB sensors, they will require a larger number of nodes since UWB sensors will be limited to less than 40 meters. This will increase the cost of implementation, but allow for greater throughput in this specific venue.

Another key piece to the QoS puzzle is developing a strategy to manage the applications that military units will be utilizing on the network. If VOIP communications or video surveillance systems are going to be utilized, the commander will need to ensure UWB or MIMO technologies are capable of providing adequate bandwidth and establishing an effective QoS scheme that will ensure the lowest latency possible. This is all contingent on the size of the unit(s) operating within an area. For example, a platoon-size unit may require connectivity for: tracking the locations and status of every Soldier or Marine on the Platoon Commander's ruggedized laptop, streaming video from every Soldier or Marine's helmet cameras, and communicating to higher over VOIP will require an extensive amount of bandwidth. Fulfilling all of these applications will possibly produce bottlenecks that prevent communication and data from filling the network "pipe". MIMO technologies have a higher possibilities of not fulfilling these services without degrading the network and increasing latency. At the end of the day, this environment naturally produces higher latency so the key will be to develop an efficient QoS scheme to lower latency as much as possible.

Finally, all UWB or MIMO devices on the tactical network need to be monitored via some type of network monitoring software for observing proper nodal functionality and maintaining the network's overall health. A tactical network with many UWB or MIMO nodes and in this type of environment, problems will arise that the users cannot repair on their own. Network management software will have the ability to query these nodes on the network for specific information. Information about connection status, packet loss, throughput, etc., can be gathered from the network nodes where this information is utilized to better the QoS of the network.

5. Secondary Research Question #4

Can UWB or MIMO radio adequately facilitate the minimum bandwidth requirements for military-structured units on the tactical edge of the network?

The answer to this question depends on several factors. As discussed in the previous question, the size of the military-structured units, types of mission, technologies being utilized, and activities within an AOR will drive this facilitation. Based on the research and simulation developed in this thesis, it is a realistic possibility that UWB and MIMO radio systems will achieve 9 Mbps throughput based on the nodal dispersion in this environment. Therefore, if a military unit's throughput requirements are below the 9 Mbps threshold and nodes are placed to provide the adequate connectivity, then UWB or MIMO radios will adequately facilitate the minimum bandwidth requirements.

6. Secondary Research Question #5

How can UWB and MIMO multiple access techniques be implemented into a tactical mesh topology?

There is a high probability that UWB signals transmitting from nodes will overlap since the proximity of the nodes are limited to a given area when multiple UWB nodes exist in an ad-hoc mobile tactical network. Therefore, UWB systems need some type of multiple access technique to manage the co-existences of these nodes. If not, the utilization of UWB technology will not be a viable wireless solution for achieving Net-centricity in a tactical network.

Some of the most common multiple access methods for the single-band approach are CDMA or TDMA. These both allow for better co-existence with other UWB nodes within the WLAN; however, the most optimal type of modulation technique for a UWB system in this type of environment is arguably OFDM. The primary advantage of OFDM over single-band schemes, such as CDMA or TDMA, is its ability to cope with severe channel conditions. An OFDM scheme discussed in this thesis worked by splitting the UWB signal into multiple smaller bands, around the 500MHz limited imposed by the FCC, and then transmitted simultaneously at different frequencies to the UWB receiver.

MIMO technologies seem like they would be easier to implement into a tactical mesh topology. MIMO communication systems can deliver interoperability solutions for existing DoD system since most MIMO technology is based on the IEEE 802.11n or 802.16e standards. Also, 802.11n and 802.16e MIMO technologies can be used with nearly all modulation or access techniques.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

The research and simulation supporting this thesis shows promise; however, additional research, testing, and implementation is required to determine which one of these wireless penetration technologies will provide the best viable solution for extending the tactical network in an austere environment. Future research should focus on conducting a field experiment to determine throughput, reliability and QoS for the UWB and MIMO radio technologies discussed in Chapter III and implement these capabilities into a tactical network architecture capable of supporting platoon-size communication and ground sensor requirements in a triple canopy environment.

1. Developing UWB and MIMO Radio System Field Experiments

As discussed in secondary research question #3, the development of an optimal network platform to properly maintain QoS issues in this network environment will take time to uncover. Field testing of the UWB and MIMO radio systems simulated in Chapter IV will provide some keen insight on how to approach possible QoS issues that could be faced in an austere environment.

The actual field testing will provide the data to validate the model discussed in Chapter IV. As discussed, SPEED did not account for the NLoS attenuation due to trees and thick foliage in an austere environment, and as a result, the radio received signal strength was calculated after the simulation results were posted. The attenuation caused by trees varies significantly depending on the shape and thickness of the foliage, and that is why this data needs to be captured through actual field testing.

The field experiment needs to also capture at which point the priority traffic experiences packet loss as mission critical streaming traffic increases over UWB and

MIMO transmissions. Packet latency and loss can be considered acceptable in some sensor applications, but this is not the case in higher-quality network service. Sensor applications that will be developed in future experiments will require a high degree of granularity and fidelity; thus, they cannot accept too much packet latency or loss. As a result, this experiment needs to provide qualitative validity with the QoS capabilities for the different wireless penetration technologies proposed in this thesis. By using IxChariot, the QoS capabilities will be measured by using their proprietary metrics such as: bandwidth, packet delay, packet loss, and jitter for different services utilized on the battlefield. The desired result is an acute understanding on how the overall performance of the network is affected when multiple systems are actively using tactical network resources in an austere environment. The following is a recommendation for developing a test plan.

a. Site Selection

The site selection for the field testing UWB and MIMO radio systems should be planned for a location close to NPS. This will allow companies or laboratories, such as Silvus or LLNL, the flexibility to support field testing based on their contractual obligations or when finished with prototype development. Monterey's environment doesn't have the overhead canopy synonymous with the austere environment in this thesis; however, it does have thick foliage and wooded forest. These are the key properties for multipath mitigation purposes. Jack's Peak Park, illustrated in Figure 43, could be used as a practical test site candidate for establishing a consistent environment for testing.

Figure 40. Jack's Peak Park in Monterey, CA [from: Jack's Peak Park, 2007]

b. Test Set-up and Methodology

The test set-up, illustrated in Figure 44, is fairly simple. The test will require the following equipment: three laptop computers, a switch, four Ethernet cables, and two UWB or MIMO radios per test. Start by establishing connectivity between the radios. The testing distance between the radios should be initially 300 meter apart, and moved closer in increments of 25 meters until connectivity is established. Antenna heights should simulate actual application of the device. For example, if using for radio communications, one radio could be positioned to ensure the total antenna height of 8 inches to simulate ground emplacement of a mesh node while the other radio is set at 3 feet to simulate a radio mounted on a tactical vest.

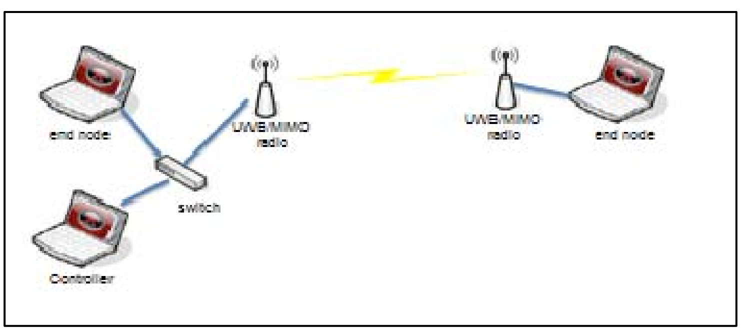

Figure 41. Set-up for UWB and MIMO radio testing

Once connectivity is established, the QoS capabilities of the radio systems need to be evaluated. The author suggests installing and using IxChariot on the three computers as the means for evaluating device and system performance for this test. IxChariot offers thorough network performance assessments and device testing by simulating hundreds of protocols across thousands of network endpoints. Although the testing requirement does not encompass hundreds of endpoints, the network tool is still applicable for the connection testing from one node to another in this test. The controller will be able to set the parameters to generate data traffic between the end users. Data traffic should simulate video streaming, information data, e-mail, or any parameter desired using IxChariot. Once testing is complete, IxChariot will provide an analysis of the QoS and performance of the UWB and MIMO radio systems.

2. Interoperability of UWB and MIMO Technologies

The compatibility between UWB and MIMO technologies and current tactical mesh networks is an area that will require additional research. As the battlefield expands in an austere environment, the tactical network will experience an increase in traffic flow across these UWB and MIMO wireless technologies. These technologies appear more capable of handling the throughput and connectivity issues associated with an austere environment; nevertheless, if these technologies are not fully integrated and tested, they may impose significant restrictions for the warfighter.

The ability to successfully integrate these technologies without degrading the availability or reliability of critical information flow will be critical to the success of achieving a NCO type of environment. For this reason, various UWB and MIMO interoperability tests must be conducted within the current TNT architectures to discover the feasibility of full capacity integration. The TNT experiment conducted in Stennis, MS will provide an adequate simulation and testing environment for these experiments. Scenarios should be developed that will test overall performance of the UWB and MIMO integration and overall network performance.

As discussed in Chapter V, one scenario could be implementation and testing of Trident's UWB UGS and mesh radios into the TNT. As illustrated in Figure 44,

Trident's UWB mesh system can be emplaced within a 300 square meter area of the woods, while the SURCs travel up and down the river providing the connectivity to the TOC utilizing a wireless 802.11a OFDM mesh. Trident's UGSs will increase the TNT situational awareness during riverine operations by providing movement detection, video streams, still pictures, and other data. This data will need to be shared with other TNT operation centers via satellite of wired connection to help build the overall COP. Another layer to this interoperability test could be introducing redundant voice communications through existing military radios. Trident's RNIC could be used as the device interface for the existing military radios. The RNIC will provide the capability to communicate and pass messages and text by integrating existing military radios into Trident's UWB Mesh Network and back to the TOC.

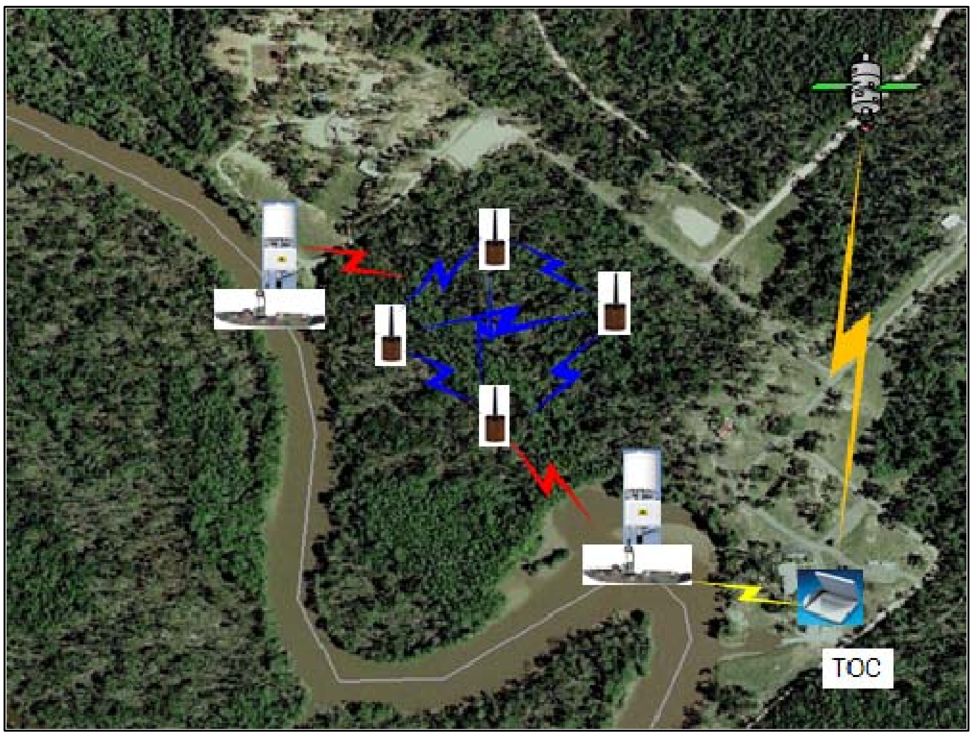

Figure 42. Future TNT implantation for Stennis, MS

This extension of the network will require robust monitoring and control in order to provide the seamless updating of all participants with data and video streams for real-time riverine operations. Management software, such as SolarWinds or DopplerVue,

could be used to monitor the network and measure the capabilities of receiving and transmitting data through SURC relays and evaluate the network by testing data throughput from node to node. Once the data is collected, publish the results.

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